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Robert S. Kerr Environmental Research Lab.
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NONPOINT SEDIMENT PRODUCTION IN THE COLUSA BASIN DRAINAGE AREA, CALIFORNIA

by

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This investigation was carried out in two phases from October 1977 to March 1982. The details on field, laboratory, and computer simulation have been reported in four comprehensive annual reports.

The production and transport of sediments from, through, and out of this basin are complex. They are affected by natural as well as man-induced factors and conditions. This investigation provided a unique opportunity to monitor and evaluate sediments in an integrated one-million acre agricultural and watershed systems. The perspective gained is different from investigations involving smaller subwatersheds and field plots.

The natural hydrologic conditions during the four-year investigation began with record-breaking rainfall (1977-78) following two years of severe drought, a relatively dry year (1978-79), an above average rainfall year (1979-80), and a below average rainfall year (1980-81). Conversely, total irrigated crop acreages as well as diverted irrigation water supply increased over the four-year period. This was mainly due to gradual increased acreages planted to rice. All other crops tended to remain the same. We have evaluated our findings to reflect longer term conditions taking into consideration the above-mentioned hydrologic and cropping variations. This final technical completion report contains Conclusions and Recommendations, and major findings of our field, laboratory, and computer studies.

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It is hereby declared that the contents of this report do not necessarily reflect the opinion of our cooperators and collaborators nor the University of California. Any opinions expressed herein are solely those of the project investigators.

FOREWORD

EPA is charged by Congress to protect the Nation's land, air and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management and the control of toxic substances, pesticides, noise, and radiation, the Agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life. In partial response to these mandates, the Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, is charged with the mission to manage research programs to investigate the nature, transport, fate, and management of pollutants in groundwater and to develop and demonstrate technologies for treating wastewaters with soils and other natural systems; for controlling pollution from irrigated crop and animal production agricultural activities; for developing and demonstrating cost-effective land treatment systems for the environmentally safe disposal of solid and hazardous wastes.

This report contains the major findings and recommendations for best management practices to control nonpoint source sediment production in the Colusa Basin Drainage Area, California. The investigation provided a unique opportunity to monitor and evaluate sediment production in an integrated one-million acre agricultural and other multi-use watershed system. The methodology utilized in this study can be adapted to the evaluation of control programs in other large multi-use agricultural watersheds. This report should benefit environmental managers as they identify and implement pollution control strategies relevant to western irrigated agriculture.

Clinton W. Hall

Clinton W. Hall, Director
Robert S. Kerr Environmental
Research Laboratory

ABSTRACT

This report contains our major findings and recommendations on "Nonpoint Sediment Production in the Colusa Basin Drainage Area, California." This investigation was carried out in two phases from October 1977 to March 1982. The details on field, laboratory, and computer simulation have been previously reported in four comprehensive annual reports.

The production and transport of sediments from, through and out of this basin are complex. They are affected by natural as well as man-induced factors and conditions. This investigation provided a unique opportunity to monitor and evaluate sediments in an integrated one-million acre agricultural and watershed system. The perspective gained is different from investigations involving smaller subwatersheds and field plots. Sediments produced at one site may be deposited at another site and the deposited sediment, in turn, may be resuspended and transported further downstream to another site. Deposited sediments as well as newly eroded materials may be transported through the entire basin as in severe storm runoff.

The natural hydrologic conditions during the four-year investigation may not be entirely representative of long-term conditions. However, the investigation began with record-breaking rainfall (1977-78) following two years of severe drought, a relatively dry year (1978-79), an above average rainfall year (1979-80), and a below average rainfall year (1980-81). Conversely, total irrigated crop acreages as well as diverted irrigation water supply, as in the Glenn-Colusa Irrigation District, increased over the four-year period. This was mainly due to the gradual increased acreages planted to rice. All other crops tended to remain the same. We have evaluated our findings to reflect longer term conditions taking into consideration the above-mentioned hydrologic and cropping variations. This final technical completion report contains Conclusions and Recommendations, and major findings of our field, laboratory, and computer studies.

This report is submitted in fulfillment of Grant Nos. R 805462 (Phase I, 1977-79) and R 807169 (Phase II, 1979-82) by the Department of Land, Air and Water Resources, University of California, Davis, under the sponsorship of the United States Environmental Protection Agency.

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CONVERSION FACTORS FOR METRIC AND ENGLISH UNITS

To convert column 1 to column 2, multiply by	Column 1	Column 2	To convert column 2 to column 1, multiply by
LENGTH			
0.621	kilometer, km	mile, mi	1.6093
3.281	meter, m	feet, ft	0.3048
0.0394	millimeter, mm	inches, in	25.4
AREA			
247.1	square kilometer, km^2	acre, ac	0.004047
0.004047	square meter, m^2	acre, ac	4,047.
VOLUME			
8.10×10^{5}	cubic kilometer, km^3	acre-feet, ac-ft	1.234×10^{-6}
0.00081	cubic meter, m^3	acre-feet, ac-ft	1,234
MASS			
1.102	ton (metric)	ton (English)	0.9072
2.205	kilogram, kg	pound, lb	0.454
YIELD OR RATE			
0.0045	tons(metric)/square kilometer, ton/km^2	tons (English)/acre	224.17
0.112	ton (metric)/square kilometer, ton/km^2	pound/acre, lb/ac	8.922
4.46	kilogram/square meter, kg/m^2	ton (English)/acre	0.22
8.922	gram/square meter, g/m^2	pound/acre, lb/ac	0.112
0.892	kilogram, hectare, kg/ha	pound/acre, lb/ac	1.12
FLOW			
0.00981	cubic meter/hour, m^3/hr	cubic feet/second, cfs	101.9
4.403	cubic meter/hour, m^3/hr	U.S. gallons/minute, gpm	0.227
1.699	cubic meter/second, m^3/s	cubic feet/second, cfs	0.0283
MISCELLANEOUS			
3.2808	cubic meter/square meters, m^3/m^2	acre-feet/acre, ac-ft/ac	0.3048
1.359	kilogram/cubic meters, kg/m^3	tons (English) acre-feet, tons/ac-ft	0.735
1.0	milligram/liter, mg/ℓ	parts per million, ppm	1.0

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SECTION 1

INTRODUCTION

Soil erosion and sediment production are of concern from at least two different perspectives. On the one hand, denudation and surface soil loss can affect productivity of lands devoted to food and fiber production. On the other hand, soil erosion and discharge of sediments from land uses can affect the quality of receiving waters and hence, the beneficial uses of waters. Although the specific aims for controlling erosion and sediment production may differ between these two perspectives, they have a common goal of protecting and maintaining the quality of our soil and water resources. This project was conceived with these two perspectives in mind, with an emphasis on the drainage watershed.

The Colusa Basin Drain (CBD) (Figure 1) conveys flood runoffs and irrigation return flows from about one million acres of watershed (upland) and agricultural (valley floor) lands on the west side of the Sacramento Valley in California. CBD has a reach of about 70 miles (Figure 2) with peak channel flows near Knights Landing of over 8,500 cfs and substantial bank overflow during the largest storm runoffs, and from less than 500 to over 3,000 cfs during the irrigation season. Flows during the nonirrigation season are quite variable, depending on intensity and duration of the storm. A portion of the drain water in CBD is discharged into the Sacramento River via the outfall gates near Knights Landing, and the remainder into the Yolo Bypass via the Knights Landing Ridge Cut (Figure 2). Water conveyed by the Yolo Bypass is eventually discharged into the Sacramento River above Rio Vista. During high water stage heights in the Sacramento River at Knights Landing, the outfall gates are closed to prevent backflow into CBD and drain waters are diverted into the Yolo Bypass.

The Sacramento River system and its reservoirs play a major role in both the California State Water Plan and the Federal Central Valley Project. The quality of the waters of the Sacramento River system is affected by storm runoffs, irrigation return flows, municipal and industrial wastewater discharges, and seawater intrusion into the Sacramento-San Joaquin Delta (Calif. DWR, 1962). Upstream of the city of Sacramento, CBD is one of the main sources of agricultural return flows discharged into the Sacramento River (Merrill et al., 1977).

It was proposed that this investigation identify the potential nonpoint sources of suspended matter in the Colusa Basin Drainage Area, to understand the factors contributing to or affecting suspended solids loading, and to develop recommendations for best management practices. Phase I (1977-79)

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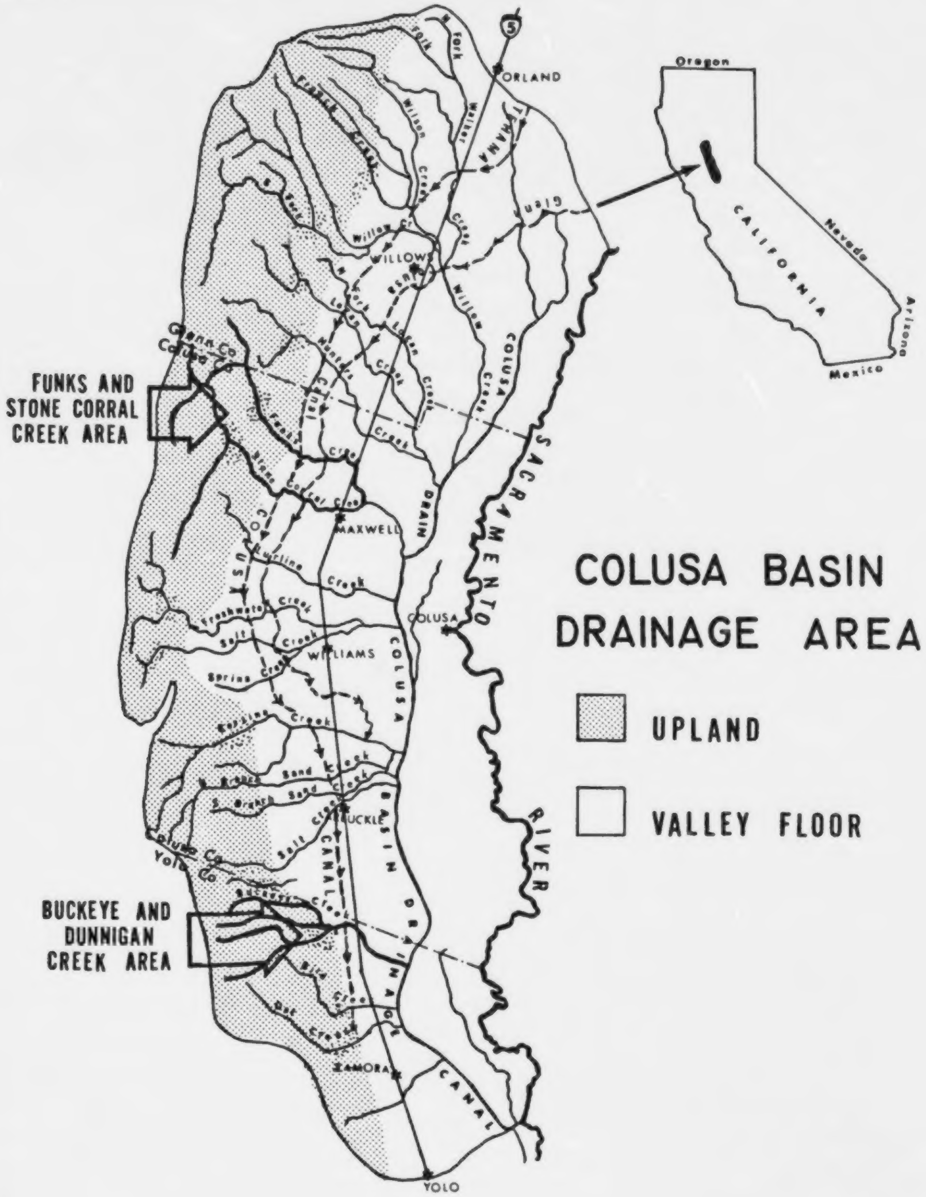
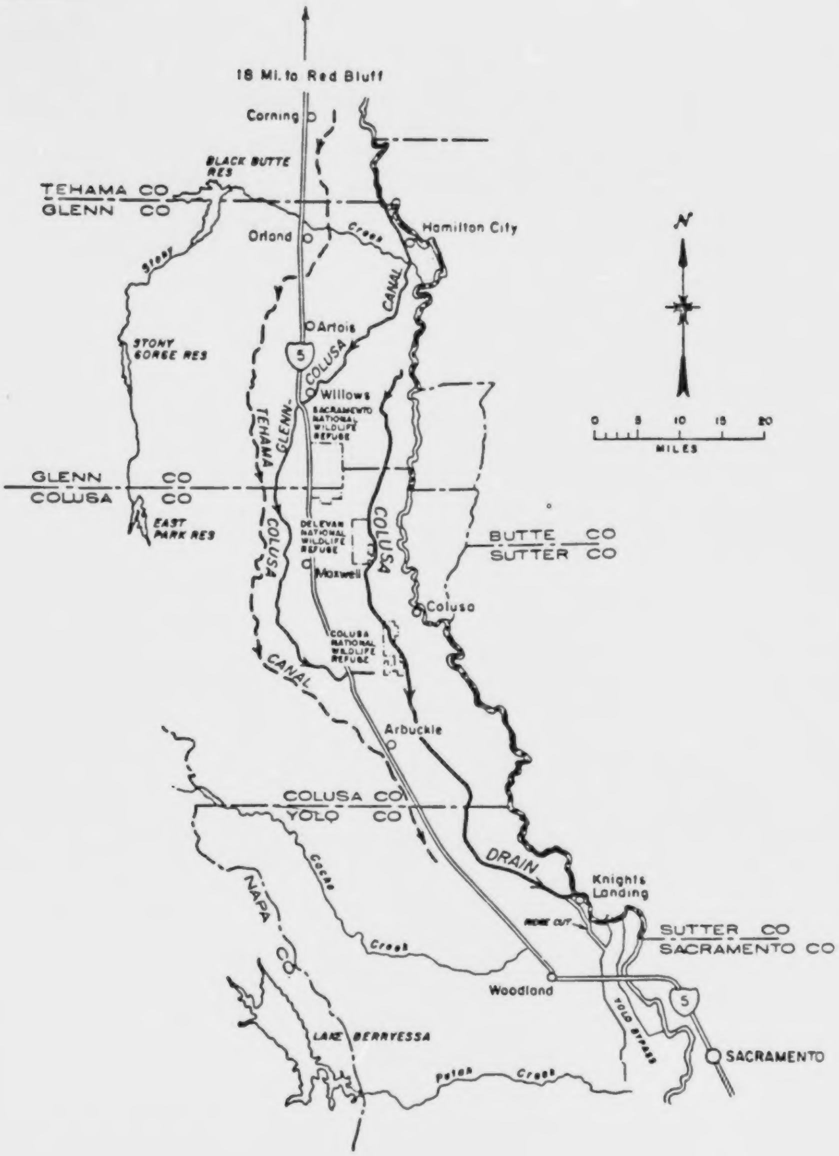

COLUSA BASIN
DRAINAGE AREA
UPLAND
VALLEY FLOOR
FUNKS AND
STONE CORRAL
CREEK AREA
BUCKEYE AND
DUNNIGAN
CREEK AREA
ORLAND
WILLOWS
MAXWELL
COLUSA
WILLIAMS
ARBUCKLE
ZAMORA
YOLO
SACRAMENTO RIVER
COLUSA BASIN DRAIN
COLUSA BASIN DRAINAGE CANAL
TEHAMA
GLENN
Glenn Co
Colusa Co
Yolo Co
5
Oregon
Nevada
Arizona
Mexico
CALIFORNIA

Figure 1. Location map of study area delineating upland and valley floor areas and major streams and canals.


18 Mi. to Red Bluff
Corning
BLACK BUTTE RES
TEHAMA CO
GLENN CO
Orland
Creek
Stony
Hamilton City
CANAL
Artois
5
COLUSA
STONY GORGE RES
Willows
SACRAMENTO NATIONAL WILDLIFE REFUGE
GLENN-
TEHAMA
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0 5 10 15 20
MILES
GLENN CO
COLUSA CO
EAST PARK RES
DELEVAN NATIONAL WILDLIFE REFUGE
COLUSA
COLUSA
Maxwell
BUTTE CO
SUTTER CO
Colusa
COLUSA NATIONAL WILDLIFE REFUGE
CANAL
Arbuckle
COLUSA CO
YOLO CO
Cache
NAPA
CO
DRAIN
Knights Landing
RIDGE CUT
SUTTER CO
SACRAMENTO CO
Creek
Woodland
5
YOLO BYPASS
LAKE BERRYESSA
Putah
Creek
SACRAMENTO

Figure 2. Location map of the Colusa Basin Drain in relation to the Sacramento River and Glenn-Colusa and Tehama-Colusa canals (USBR, 1974b).

would involve an overview analysis of sediment production and transport based upon interpretation of available information and data, and the conduct of selected field and laboratory studies to identify the reason(s) for the sediment problem in the study area. Phase II (1979-81) would involve intensive quantitative investigations of the more important factors or probable causes of the turbidity problem and development of recommendations for alternative management for sediment control in the study area. Phase II activities were extended to monitor water and sediments in selected sites for a limited number of pesticides.

The specific objectives of this project are:

1. Appraise areawide soil erosion and sediment production in the Colusa Basin Drainage Area.
    a. Subdivide the 1,655 square mile study area into subwatershed units.
    b. Characterize each subwatershed unit and identify the probable sources of sediments.
    c. Estimate potential erosion and sediment production in each subwatershed unit.
2. Conduct field investigations on suspended matter production and transport.
    a. Identify the nature and sources of suspended matter.
    b. Monitor CBD, Glenn-Colusa Irrigation District (GCID), and selected tributaries during irrigation and nonirrigation seasons.
3. Ascertain the factors contributing to or influencing erosion and suspended solids production, and the transport, deposition, and resuspension of sediments.
    a. Determine soil erodibility of selected soil types including laboratory studies on the "K factor" in the Universal Soil Loss Equation and the slope steepness, "S factor."
    b. Determine the physical, chemical and mineralogical, and biological characteristics of suspended and bed load materials at selected sites and seasonal periods.
    c. Appraise the irrigation management and drainage practices including the conduct of on-farm sediment production tests.
    d. Conduct biological surveys of the waters in the study area to ascertain the relative importance of biological organisms and biological factors contributing to the turbidity problem.

e. Conduct a pesticide residue survey for selected chemicals that are commonly used in the study area.

4. Develop a sediment transport model.

5. Develop recommendations for best management practices for an integrated watershed-irrigated agriculture nonpoint source control on suspended matter production in the study area.

6. Consult with and inform interested parties and agencies on research plans and progress made, and obtain reviews on proposed management or control options for feasibility and implementation.

The California State Water Resources Control Board (SWRCB) is responsible for developing water quality management planning for nondesignated areas as required by Section 208 of PL 92-500. The SWRCB has singled out sediment studies as one of four programs receiving high priority planning issues and budgeting for agriculture (SWRCB, 1977). For the nondesignated area in the Central Valley of California, the Regional Water Quality Control Board-Central Valley Region is the principal planning agency. This Regional Board has delegated the sediment management program to the Soil Conservation Service (USDA, 1978a). The Soil Conservation Service (SCS) and local Resource Conservation Districts (RCD) have carried out eight Pilot Sediment Projects in the Central Valley, one of which is located in the Colusa Basin Drainage Area (USDA, 1978b). The site of this pilot study is in the Buckeye Creek-Dunnigan Creek drainage area in northeastern Yolo County (Figure 1). The state office of SCS and the Yolo RCD have formulated best management practices to control or reduce soil erosion and sediment production, and proposed their implementation (USDA, 1979b). The activities of this project were coordinated with the SCS pilot study. The project results are expected to contribute to current and future 208 planning efforts as well as meeting the mandates of the State of California Porter-Cologne Water Quality Act.

SECTION 2

CONCLUSIONS

The conclusions are arranged in accordance with sediment sources and yield; sediment components and sizes; factors (physical, chemical, mineralogical, biological) controlling sediment transport; sediment as a pesticide carrier; and sediment transport modeling. These conclusions are generated from four years of field, laboratory, and computer studies of sediment production and transport in the one-million acre Colusa Basin Drain (CBD) study area in the Sacramento Valley, California.

A. Sediment Sources and Yield

Analysis of the watershed indicates that four potential sources of sediment yielding erosion processes exist: sheet and rill, channel, gully, and roadway erosion. Gully and roadway erosion were not specifically studied.

1. Sheet and Rill Erosion

a. Sheet and rill erosion from upland and dry-farmed areas are the main potential sources of erosion in the study area.

b. These types of erosion result from kinetic energy of raindrop impact, and from the forces of flowing water exerted on the soil surface on irrigated and nonirrigated lands.

c. The Wischmeier and Smith Universal Soil Loss Equation (USLE) was used as the basis for estimating sheet and rill erosion. Six independent variables were estimated for use in the USLE. These were the rainfall erosivity parameter, R, soil erodibility value, K, a slope length factor, L, a slope angle factor, S, a cover factor, C, and an erosion control practice factor, P.

d. The average potential soil loss calculated for the 24 watersheds in the basin using USLE was 268,920 tons per year or 180 tons per square mile. We used the USLE to estimate a potential soil loss of 42,649 tons per year for Stone Corral Creek. Based on weekly measurements of channel water flow and suspended sediment, the monitored sediment discharge was 344,920 tons and 51,940 tons per year in 1980 for CBD and Stone Corral Creek, respectively. The USLE underestimates the soil loss or sediment discharge by about 20 percent. During the four year study from October 1977 to October 1981, the total sediment discharge from CBD was 1,112,540 tons or an average of 278,140 tons per year in CBD which is in close agreement with the potential soil loss estimated by the USLE.

e. Slope steepness was a critical parameter in estimating potential soil losses from the western portion of the basin. The Contra Costa and Hillgate soils from the Colusa Basin Drainage Area were used for measuring soil loss at slopes between 3 and 50 percent. The results from rainfall simulation studies indicated that as slope increased beyond 40 percent, the effect of slope on erosion was decreased. This was possibly due to changes in the erosion process.

f. The sheet and rill erosion, and sediment production from irrigated agriculture (tomato, corn, and rice fields) were measured.

   (1) The sediment load produced from the first irrigation of a 30 acre tomato field was 1.6 tons as measured at the weir in the tailwater collection ditch, and 2.9 net tons measured at the drain canal. The net unit mass emission of sediment during this irrigation was 190 lbs/ac. The sediment discharge from the second irrigation was 0.7 tons, and the unit mass emission was 60 lbs/ac.

   (2) A similar test on an 11 acre furrow irrigated corn field gave sediment production of 2.1 tons, or a net sediment yield of 250 lbs/ac from the corn field for one irrigation.

   (3) In contrast to furrow irrigated tomato and corn fields, the flooded rice fields act as settling basins for suspended sediment. The sediment discharged from six fields varied from 36 to 330 lbs/ac, or 7 to 33 percent of that portion brought in with the supply water for the entire growing season.

   (4) The concentration of suspended sediment in the CBD indicated that the bulk of the sediment was deposited at intermediate locations wherever the entraining runoff waters were insufficient to sustain transport. This deposited sediment was transported to CBD by accelerated streambed erosion during the winter runoffs.

2. Channel Erosion

   a. Channel erosion refers to the removal of sediment from the channel banks and bed by shearing forces of water. This type of erosion or sediment production frequently occurs from the channel banks and the channel overflow areas without protective cover. Channel meander development produces a sequence of equally developed bends to the right and left which causes secondary currents with higher shear stress than would occur with a straight line flow pattern. These also cause bank erosion.

b. Accelerated channel erosion was observed in Stone Corral and Buckeye Creeks during the period of high rainfall runoffs.

c. The bed materials taken at specific sites along Buckeye Creek were subjected to particle size analysis. The difference in size distribution of bed sediment between the 1978 and 1979 study periods indicated that channel erosion occurred in the Buckeye Creek area between these two dates.

d. A three-mile reach of Stone Corral Creek was monitored for channel erosion during May and September 1978. Suspended sediment produced from within this reach of Stone Corral Creek was measured as 190 tons during May, and 290 tons during September. The source of in-channel sediment production appears to be bed deposits from previous winter runoff events.

3. Gully Erosion

This type of erosion results from accumulations of water in narrow channels. We view gully erosion as point sources of sediment. Control measures can be devised for each gully.

4. Erosion from Roadways

Erosion from transportation facilities, especially unpaved roads and shoulders of paved roads, can either be viewed as point sources or as causes of sheet, rill and gully erosion for which special management practices are needed.

B. Sediment Components and Sizes

1. Analysis of water samples taken from CBD and its tributaries indicate that on the average the suspended sediment was comprised of 60 percent mineral material, 30 percent organic matter, and 10 percent algae.

2. Suspended algae was maximum in Stone Corral Creek due to discharge of water from the rice fields. It was minimum in the lower reaches of CBD due to higher settling rate and endogenous respiration of algae.

3. Suspended organic matter in CBD water consisted, on the average, of 60 percent biodegradable organic matter and 40 percent refractory organic matter.

4. Suspended mineral sediments were mainly silt and clay with smaller fraction of sand. Clay mineral species were identified as smectite, chlorite, mica, kaolin, and hydroxy-interlayered chlorite-vermiculite.

5. The results of the particle size analysis of the bedload sediment in the stations of CBD indicate an areawide uniform distribution of grain sizes. The bedload sediment was about 60 percent sand size material with lesser silt and clay and low percentage of gravel. The bed material of the Sacramento River at the CBD outfall changed from larger size gravel and sand material upstream of the outfall to smaller size sand downstream due to discharge of water from CBD into the Sacramento River.

6. The organic matter of the bedload sediment varied from 10 to 30 percent in CBD and its tributaries.

C. Factors Contributing to and/or Affecting Sediment Production and Transport

1. Physical Factors

a. Hydraulic characteristics which are related to the flow pattern, flow rate, bed configuration and roughness, current velocities, fluid shear stress, critical shear stress of the bed material, and water depth were the factors controlling sediment production, transport, and deposition.

b. The Reynolds number for the flow pattern in CBD ranged from 0.12×10^5 to 47×10^5 from 1977 to 1980. The flow was turbulent at all times in the study area.

c. Current velocity ranged from 0.2 to 4.6 ft per sec (fps) for the CBD-1 stations. Current velocity was maximum at CBD-3 (Colusa riffles area) and minimum at CBD-1A (lower reach).

d. The fluid bed shear stress ranged from 0.3 to 22 $\mathrm{dynes/cm^2}$. It followed the same pattern as current velocity profile along CBD. The critical shear stress of the bed material was 10 $\mathrm{dynes/cm^2}$. For peak storm runoff, the bed shear stress exceeded the critical shear stress and channel erosion took place along CBD. The bed shear stress was lower than the critical shear stress for the irrigation and nonirrigation seasons, except for storm runoffs. Net deposition took place along CBD, mainly at CBD-1A where the shear stress was minimum and current velocity was lowest.

e. Particle size analysis of the bed material taken along CBD indicated a net deposition of sediment occurred on the channel bed from 1977 to 1980.

f. Flow rate was another factor controlling suspended sediment in CBD. The flow rate ranged from 170 to 10,900 cfs, and suspended sediment ranged from 11 to 1,450 mg/ℓ for the CBD-1 outflow station. The sediment discharge and hydrograph showed that the flow rate and sediment concentration increased or decreased simultaneously. The magnitude to which the sediment discharge changed simultaneously with water discharge was different for the irrigation season than for the nonirrigation season. During the nonirrigation season the fine sediment fractions that form the washload of a stream, originating from sheet and rill erosion, were readily entrained in runoff. The greater the runoff the higher the sediment discharge. During the irrigation season a large quantity of water with low sediment concentration drained from the rice fields and diluted the suspended sedment concentration.

g. During the period from October 1977 to October 1981, 4,046,600 ac-ft of water was discharged through the CBD-1 outflow station. During the nonirrigation seasons from 1977 to 1981, 2,583,810 ac-ft of water or 31 surface inches was discharged. Over this same period, the total average precipitation (1977-1981) was 65 inches as recorded at the Sacramento National Wildlife Refuge, Williams, and Dunnigan sites on the valley floor.

h. Development of the functional relationships between suspended sediment and its physical factors indicate that suspended sediment was exponentially related to current velocities, flow rate, and water depth. However, the suspended sediment was linearly related to flow rate and current velocity when the flow rate was less than 5,000 cfs with somewhat different relationships between summer and winter flows. The erosion of the bed material occurred particle by particle, and aggregate by aggregate. A massive erosion of bed material or soil surface took place at flow rates greater than 5,000 cfs so that a linear correlation of suspended sediment with current velocity and flow rate changed to an exponential one.

2. Chemical Factors

a. Chemical factors affecting dispersion, flocculation, and sedimentation of cohesive suspended particles in the drain are the concentration of soluble ions expressed as total dissolved solids (TDS) or electrical conductivity (EC), sodium adsorption ratio (SAR), and acidity (pH) of the water.

b. The EC of storm runoff waters ranged from 140 to 440 micromhos per centimeter (μmhos/cm). The average EC of the supply water (main canal) was 195 μmhos/cm. The EC of the drain water ranged from 460 to 1,170 μmhos/cm. There was a tendency for salinity to increase from CBD-6 (upstream) to CBD-1 (downstream).

c. The SAR varied from 0.4 to 6.0. The SAR of the supply water was 0.5, and the SAR of the drain water ranged from 2.0 to 6.0. The SAR increased from the main irrigation canal to CBD and remained constant along the drain.

d. The TDS ranged from 150 to 800 milligrams per liter (mg/ℓ), with an average of 400 mg/ℓ at CBD-1 and lower values at the other stations. The salinity of water was lower during the storm runoffs and during August. This was due to dilution resulting from the high precipitation runoff and drainage from the rice fields before harvest, respectively.

e. The concentration of dissolved ions in the drain system did not have a significant effect on particle settling rate. A settling velocity test on the coarse-sized bed material with and without sodium phosphate (Na_3PO_4) treatment showed that settling velocity of the particles were controlled more by physical rather than chemical factors.

f. The experiment on the effect of sodium (Na) on soil erodibility revealed that Na decreased aggregate stability which increased susceptibility to rainfall detachment. Erodibility of Colusa Basin soils (Contra Costa and Hillgate) increased significantly with the addition of as little as 2 percent Na on the exchange complex.

g. The pH values for all water samples from the study area ranged from 7.4 to 8.5. About 40 percent of suspended particles in the drain was organic matter with pH-dependent charges. Since the pH was greater than 7.0, all organic particles are negatively charged and behave similar to clay particles. The pH seems to stabilize the negatively charged particles in the system, and reduce flocculation and sedimentation.

h. The 1981 summer water discharged from CBD significantly changed the salinity of the Sacramento River water. The average EC of the river water inside the plume was 390 µmhos/cm in contrast to the average EC of 170 µmhos/cm outside the plume. These measurements were conducted at Bascule Bridge, about 200 meters downriver from the mouth of the drain.

i. The average turbidity of mixed CBD and river waters during the 1981 summer at inside the plume was 35 Jackson Turbidity Units (JTU), and the average turbidity of the river water at outside the plume was 15 JTU. Changes in the turbidity of the river water was higher during late May and September due to the high rate of discharge of water from CBD to the river.

j. The 1981 summer water discharged from CBD changed the color of the river water. The average true color of the water inside the plume was 18 chloroplanate units (CPU), and outside the plume, 10 CPU. The color change was maximum in late September due to the increased water discharged from the rice fields, and CBD waters containing a high concentration of organic particles. A least squares fit to the turbidity, pH, and color data revealed that color changed linearly with turbidity and pH.

3. Biological Factors

   a. Contribution of biological factors to sediment production or resuspension in CBD was important. Benthic organisms including fish live in and are in continuous motion in the bottom sediments. The result of such movement was the resuspension of bottom sediment.

   b. An extensive study during the summer of 1978 and 1979 indicated that suspended sediment was greater in CBD-1 than at CBD-2. The physical factors contributing to the sediment production were greater at CBD-2 than at CBD-1. This anomaly may be attributed to the biological activities of organisms, mainly carp, in the drain.

   c. Two organisms, carp (*C. carpio*) and crayfish (*O. viriles* and *P. clarkii*), seem to significantly affect the turbidity of CBD water. The carp was known to increase turbidity through resuspension of finer particles while foraging. Crayfish cause resuspension of sediments through burrowing activity and/or general locomotion.

   d. The contribution of biological factors to the 1980 summer suspended sediment was evaluated through calibration of the sediment transport model. It was estimated that aquatic organisms contributed between 0 and 20 percent of the total suspended sediments.

4. Mineralogical Factors

   a. Clay-size (<2 μm) particles constituted over 50 percent of the suspended mineral load in CBD throughout the year. Relative proportions of clay decreased immediately following drainage of rice fields in the fall.

   b. Clay-size phyllosilicate layer mineral species are similar in kind and relative abundance in CBD suspensions, irrespective of location and season.

   c. Chlorite and kaolin were the dominant phyllosilicate species in coarse clay (2-0.2 μm) fractions. Smectite was the dominant phyllosilicate species in fine clay (<0.2 μm) fractions in suspended mineral matter. Mica, smectite and vermiculite-chlorite intergrade occur in lesser quantities in coarse clay. Kaolin accompanies smectite in fine clay fractions.

d. Mineralogy of clay in bedload material within CBD was similar to mineralogy of suspended material.

e. Calcium (Ca) was the dominant cation adsorbed by the cation exchange complex of suspended material within the CBD. Exchangeable magnesium (Mg) was less than exchangeable Ca but higher than exchangeable potassium (K). Exchangeable Na constituted a small proportion of exchangeable cations although Na was, in most cases, the dominant soluble cation in the CBD suspensions.

f. Adsorption specificity exhibited by clays in the Basin system slightly favored Ca over Mg, and greatly favored Ca and Mg over Na.

D. Sediment as a Pesticide Carrier

1. Of the four chemicals, 2-methyl-4-chlorophenoxyacetic acid (MCPA), Molinate, Ethyl Parathion and Methyl Parathion investigated in this study, MCPA, Molinate and Methyl Parathion appeared in significantly measurable concentrations in CBD.

2. Emission of chemicals into the water courses investigated appeared to be site specific and time specific.

3. Application of three times more Molinate than MCPA resulted in significantly higher concentration of the former in drain waters. Peak concentrations of Molinate were ten times greater than MCPA.

4. Emission of Molinate occurred mainly in May and June corresponding to the same period of application. However, emission also appeared related to increased suspended sediment and water outflow during this same period indicating a possible relationship to management practices.

5. The total amount of Molinate transported into the water courses by sediment was small compared with the amount in the aqueous phase. However, the concentration adsorbed in the sediment was greater than the concentration in the aqueous phase. The degree of saturation of the sediment with chemical was a function of the concentration of chemical and sediment in the aqueous phase.

6. At lower chemical concentrations in the aqueous phase and higher concentrations of sediment, the emission of chemicals in the sediment phase could be a significant percentage of the total emission of chemical.

7. Spatial and time surveys indicated the complex interaction of variations in timing of application, sources of chemical and water outflow, variations in drain flow and probable biological and sedimentation processes that occur in the system.

8. It was not possible to ascertain the extent of chemical contamination of drain waters resulting from drift and other inadvertent sources during application of the chemical to adjacent fields.

E. Mathematical and Computer Simulation Model

1. A one-dimensional computer model was developed and applied to a 20-mile lower reach of CBD. This model simulated parameters such as suspended mineral sediment, suspended organic matter, suspended algae, total suspended sediment, ammonia, nitrate, and orthophosphate.

2. The computer model was based on a mass balance equation that included advective transport, diffusive transport, erosion and deposition, chemical and biological transformations, and inflow of point and nonpoint sources. The mathematical solution was based on a finite-difference implicit method.

3. In regard to model capability, time and distance intervals can be adjusted to obtain any degree of resolution suitable for a given problem. The solution provides for a temporal and spatial description of the parameters to be simulated. It also provides for determining the bed shear stress, the current velocities, and the water depth.

4. The model was calibrated and validated based on the data collected in the summer of 1980 from six stations along the lower reaches of CBD.

5. The simulation results for two hydraulic parameters (current velocity and water depth) agree with measured values. The model simulated total suspended sediment within 90 ±5 percent of measured values. The simulation results for all constituents are in good agreement with measured values.

6. Sensitivity analysis indicated that the model was sensitive to flow rate, current velocities, settling velocities of particles, and the bed shear stress. In the simulation of suspended organic matter, the model was sensitive to decay rate and the settling rate of organic matter. In the case of algae, the model was sensitive to endogenous respiration of algae and half saturation constant of phosphorus.

7. A User's Manual was developed to provide information on the data input format, location of tributaries, hydrologic data (including

entering flows, incremental flows, depth-velocity-discharge coefficients), decay rate and other coefficients.

SECTION 3

BEST MANAGEMENT PRACTICES AND RECOMMENDATIONS

A. Best Management Practices

1. Practices designed to reduce erosion should not be an impediment to continued agricultural productivity. It has to be economical, and the cost shared equitably between the landowner and the downstream water users.

2. Best management practices (BMPs) may be subdivided into those which reduce soil erosion on site, and those which prevent sediment from reaching a body of water. The first is best in the long term because two goals are achieved: soil and soil productivity are preserved, and the water quality is protected. The second is necessary in the short term to minimize sediment reaching the CBD from existing problem areas. Long range solutions should rely on practices which reduce erosion at its source. Standard practices such as water diversion or sediment retention ponds can be used where appropriate.

3. On soils on the west side of the Colusa Basin with slopes greater than 30 percent, the dominant uses are range and forestry with range being the most important economically and most extensive. Studies have shown that poor management can cause deterioration of rangelands and decrease range productivity, and contribute to accelerated sediment production.

4. Livestock management on rangelands can be the most effective and least costly method of erosion control. Range practices to control soil erosion and maintain productivity of the range are grouped into three broad management types: vegetation management, facilitating as well as accelerating practices. Vegetation management includes proper grazing use, deferred grazing, and planned grazing. Facilitating practices are used to control or influence animal movements. This is done by developing water and trails, establishing walkways in wet areas, fencing, and proper location of salt licks. Accelerating practices are those that cause plant growth to be faster than under unmanaged conditions. Seeding, brush management, fertilizing, water spreading, and controlled burning are examples of accelerating practices.

5. A management program which includes acceleration of plant growth and appropriate animal management can have multiple positive benefits. The rancher who invests money in range improvement will gain extra income from the increased production in the short term. This may be offset by reduced short-term production on areas where animal numbers or grazing periods must be reduced. In the long term, the productivity on the entire range should improve. Downstream, decreased suspended sediment due to reduced erosion will benefit water users. Similar range management strategies can be used on slopes less than 30 percent.

6. For management practices such as walkways, stock trails, forage quality improvements, and fencing to be economical, the costs associated with the practices will have to produce yield benefits to the rancher who implements the practices, or the cost will have to be subsidized. Conservation management practices which result in animal yield increases have the advantage over sediment retention structures. The increased income produced offsets some of the costs involved in their implementation. The most productive best management practice will be one designed to fit a particular area.

7. The suitable means of reducing soil loss during the winter months on sloping cultivated areas are contour cropping, zero or minimum tillage agriculture, and conservation cropping systems involving rotations of grasses and legumes grown in desired sequence.

8. Soil loss can be reduced by allowing plants to remain on the surface during critical erosion periods. The plant materials intercept rainfall and lessen the effect of raindrop impact. They also reduce the bed shear stress of overland flow by increasing surface roughness.

9. Contour plowing of sloping irrigated and nonirrigated lands where tillage is necessary increases runoff detention time during storms. It increases infiltration and reduces sediment delivery.

10. Infiltration rates can be maintained or increased by reducing compaction due to excessive traffic and operation of equipment when the soil is wet, by applying chemical amendments, or by incorporating organic matter.

11. The BMP to control sediment production from irrigated lands is to minimize surface runoffs from irrigation. Minimizing tail waters would reduce the discharge of sediment, fertilizers, and pesticides from the drain system.

12. Roads have been identified as a major source of sediment. Closure of dirt roads in wet weather, permanent closure of some nonessential roads except for emergency services, and proper installation of water bars, culverts, and water spreaders can reduce sediment from roads. An appropriate practice or set of practices must be determined for each road segment to be treated.

13. Severe channel erosion may be controlled with the practice of vegetative stream bufferstrips alone or in combination with grade stabilization and inlet structures.

B. Recommendations

1. Noncultivated Steep Areas (>30 percent slope)

    a. Educational programs on the benefits of erosion control is the first step in implementing BMPs.

    b. Federal, state, and local agencies working with private individuals and organizations should implement the education process and BMPs.

    c. Improved range management including managing vegetation through proper grazing pressure and planned grazing levels, the development of water, trails for livestock, and practices which accelerate plant growth should be implemented, where appropriate and cost effective in the long term.

    d. Practices should be specific to the soil-slope-vegetation-land use problem.

    e. Where erosion problems are great, unpaved roads should be closed during wet periods, permanently closed in some cases, or rocked with suitable water control structures if roads are required to remain open in the winter period.

    f. Culverts, water bars, and water spreaders should be properly installed on roads.

2. Cultivated Rolling Areas (15 to 30 percent slope)

    a. Practices of contour cropping, cultivation, and no till or minimum tillage should be implemented to reduce runoff.

    b. Traffic should be reduced and machinery operation better timed to reduce compaction and improve water intake rates.

    c. Chemical amendments or organic matter incorporation where appropriate should be used to maintain and improve infiltration.

    d. Catchment basins should be designed to collect sediment discharge from cultivated fields.

3. Irrigated Areas

    a. Conservation cropping systems with rotation of grasses and legumes should be practiced where appropriate to keep soil covered during critical erosion periods.

b. Contour plowing on sloping lands should be implemented where tillage is necessary to reduce sediment yield.

c. Practices to reduce discharge of water and sediment should be conducted by farmers in the furrow irrigation of tomato, corn, and other row crops. One such practice is to reuse, where feasible, tailwater discharged from irrigated areas to reduce discharge of sediment and other quality components.

d. As new water is brought into the basin, and as lands formerly used as rangeland or dry-farmed land are cultivated and irrigated, the potential exists for increased soil loss by sheet and rill erosion. Careful planning and implementation of appropriate conservation practices can reduce erosion and should precede development of these lands.

4. Control Measures for Channel Erosion

a. Stream banks of Stone Corral and Funks Creeks where feasible should be reshaped and protected by planting suitable ground covering grass, and by rock structures at places where creeks bend.

b. If cost is not the restraint, rip rap at bends, large boulders with wire fences and wire revetments to reduce bank erosion, and/or a sedimentation basin should be installed in Buckeye Creek.

5. Pesticide

a. The most important management practice that would minimize outflow of chemicals from agricultural fields is to minimize outflow of water during and immediately following chemical application.

b. Apply optimum amount of chemicals in such a manner as to minimize contamination of nontarget areas.

SECTION 4

INVESTIGATION RESULTS AND DISCUSSIONS

This section presents a summary of the work completed in the four-year project to identify the potential nonpoint sources of suspended matter in the Colusa Basin Drainage Area.

Six kinds of potential erosion problems exist in the watershed. Stream bank erosion, gully erosion, sheet and rill erosion, and roadway erosion were identified by the Soil Conservation Service (SCS) (USDA, 1979a). Mass wasting and wind erosion can be added to this list. Wind erosion was not studied because it is not likely to contribute significant sediment to the Colusa Basin Drain (CBD).

We elected to concentrate our efforts on sheet and rill erosion for several reasons. First, it is a potential mechanism for sizable quantities of sediment. According to a SCS report (USDA, 1979a), 58 percent of the gross erosion and 52 percent of the sediment yield in the Buckeye Creek and Dunnigan Creek watersheds were from sheet and rill erosion. We have assumed that soil losses from these watersheds, which are part of CBD, are representative of soil losses throughout the Basin. Second, management activities or lack of management activities can accelerate sheet and rill erosion above the background or geologic rates of erosion. A corollary to this fact is that sheet and rill erosion should therefore be controllable with appropriate management practices. Third, sheet and rill erosion produces nonpoint sediment.

Gullies can be viewed as point sources of sediment, and control measures can be devised for each gully. Roadway erosion, specifically unpaved roads and shoulders of paved roads, can either be viewed as point sources or as special cases of sheet and rill erosion for which special management practices are needed.

Stream bank erosion was the second largest source of sediment in the SCS study (33 percent). In a sense, control of bank erosion or bed scour is amenable to both point and nonpoint source management practices. Specific channel locations can be treated as point sources. In addition, upstream changes in water flow regimes can reduce peak flows, average flow rates, and flow variabilities which might lead to reduced erosion. Stream bank erosion was not specifically studied in this part of the project.

The first phase of the study was to locate potential sources of sediment from sheet and rill erosion. The second phase was to determine where detailed technical studies would improve the prediction of sediment production and to do the technical studies.

POTENTIAL NONPOINT SEDIMENT SOURCE ANALYSIS

We chose to use the Wischmeier and Smith (1978) Universal Soil Loss Equation (USLE) as the basis for estimating potential erosion sources for several reasons. First, parameters for the equation from a large area (in excess of 4280 km^2) could be estimated from topographic maps, aerial photographs, and soil maps. Sufficient data for watershed models such as CREAMS (Knisel, 1980) were not available. Second, use of the USLE was consistent with other sediment production studies in the Basin (USDA, 1979a) and in California (USDA, 1979b).

In some watershed models, flow and peak flow rates are required to estimate erosion (Williams, 1975; Williams et al., 1971). We did not have flow (Q) or peak flow (Q_p) for most of the watersheds in the basin. In addition, these watersheds are larger than those used to develop the watershed models.

Another advantage of the USLE was that it contained the major important variables identified by many researchers. As an example, Anderson (1975) tested 32 independent variables and six streamflow variables. He grouped these into five major categories which are identical to five of the parameters in the USLE: precipitation (R), geology (K), topography (LS), vegetation (C), and time difference. These variables can be obtained from aerial photos and topographic maps with limited field checking.

Shown (1970) evaluated a method suggested in a Pacific Southwest Inter-Agency Committee report (PSIAC, 1968) and found that it worked well for watersheds between 0.02 to 37 mi^2. The PSIAC model rates the same parameters as the USLE in a slightly different form. These factors are surface geology, soils (K), climate (R), topography (LS), ground cover (C), land use (P), upland erosion, runoff, and channel erosion.

These examples illustrate that the major factors which need to be evaluated for estimating sediment yield were included in the USLE even though the USLE was not designed for such use.

Six independent variables are needed to estimate potential soil loss from an area using the USLE. These are a rainfall erosivity parameter R, a soil erodibility value K, a slope length factor L, a slope angle factor S, a cover factor C, and an erosion control practice factor P. Values of each factor are multiplied together for each soil unit in a watershed. The A value was multiplied by the area of the unit to determine potential erosion from the watershed.

Soil erosion from the entire Colusa Basin watershed could not be easily calculated because of the watershed's size and complexity. Twenty-four smaller watersheds were delineated on USGS 15 min topographic quadrangles. These were the basic land units of the study (Table 1). Each watershed contained numerous soil mapping units. These units were predominantly phases of soil series. Values of K, L, and S were calculated for each soil mapping unit (Tanji et al., 1980a). Values of R and C were calculated for each watershed. P was assumed to be 1.0 for all watersheds.

TABLE 1. SUMMARY OF WATERSHED AREA AND POTENTIAL SOIL LOSS

Watershed #	Name	Area			Soil Loss	
		Acres	(mi^2)	(Km^2)	(Tons)	($Tons/mi^2$)
I	Willow & Walker Creek	155,338	242.7	628.5	54,817	226
II	Logan Creek	95,030	148.5	384.6	26,902	181
III	Stone Coral Creek	81,954	128.1	331.6	42,645	333
IV	Lurline Creek	57,705	90.2	233.5	15,139	168
V	Freshwater Creek	78,103	122.0	316.1	27,299	224
VI	Sand Creek	93,505	146.1	378.4	22,499	154
VII	Salt Creek	19,498	30.5	78.9	11,197	367
VIII	College City Area	9,705	15.2	39.3	100	7
IX	Petroleum Creek	22,989	35.9	93.0	6,420	181
X	Buckeye Creek	33,493	52.3	135.4	28,634	548
XI	Bird Creek	9,163	14.3	37.1	3,329	233
XII	Oat Creek	19,498	30.5	78.9	13,280	435
XIII	Brenton Creek	13,645	21.3	55.2	6,341	298
XIV	Smith Creek	7,088	11.1	28.7	1,479	133
XV	Dufour Creek	23,294	36.4	94.2	3,444	95
XVI	Meridian Edge	5,274	8.2	21.3	1,783	217
XVII	West Canal Landing	12,787	20.0	51.7	134	7
XVIII	Maxwell Northeast Drain	6,550	10.2	26.5	67	7
XIX	Provident Drain	25,796	40.3	104.4	335	8
XX	Larkins Childrens Ranchero	64,133	100.2	259.5	863	9
XXI	Bounde Creek	14,017	21.9	56.7	198	9
XXII	Packer Road	8,025	12.5	32.5	97	8
XXIII	Harbison Grant	23,331	36.5	94.5	275	8
XXIV	Southeast Basin	94,374	147.5	381.9	1,596	11
	TOTAL (dot count)	974,295	1,522.3	*3942	268,924	
	Total (perimeter)	1,052,531	1,654.58	4286		
	Average soil loss for total watershed					177

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*Rounding error makes column and row totals slightly different.

Rainfall erosivity (R) was calculated from Equations 1 and 2:

$$R = 16.55\ p^{2.2} \tag{1}$$

$$R = 10.2\ p^{2.2} \tag{2}$$

These relate R to the maximum rainfall (p) in a 6 hour period with a two-year return interval (USDA, 1975). The Colusa Basin is within two of the SCS rainfall type regions I and IA. Equation 1 is suitable for use in Region I which includes the eastern two-thirds of Yolo and the eastern edge of Colusa and Glenn Counties. Equation 2 is to be used in Region IA which encompasses the remainder of the Colusa Basin (USDA, 1975). Data for three recording rain gauges in the basin were used to determine p (State of California, 1976). These stations are at low elevations and we are likely to have underestimated the R value for the higher parts of the watersheds.

We used rounded average values of R as was done by SCS (1979a,b). Values under 12 were given an R of 10, from 13 to 17, R = 15, and for 18 to 22, R = 20. In the SCS study (1979a,b) values for two-year-six-hour isopluvials were used to obtain R values of 40. We relied on data from existing gages and this may be a major source of error in this analysis. We know that rainfall amount increased with elevation but there were few data with which to make good estimates of R. We did assume a 50 percent increase in R for upland soils, but this did not give results as high as the 40 used in the SCS reports (1979a,b). We estimate that the error in these upland R values may be as much as 50 percent and for individual years may be as much as 100 percent. The level areas of the basin will have lower errors, but the error may still be as high as 20 percent (Table 2).

Each soil has a combination of properties which makes it resist rainfall impact to a greater or lesser extent. Soils which have poor aggregate stability or are high in silt are highly erodible and have large K values. Soils which have stable aggregates or are low in silt tend to be less erodible and have low K values. The allowable range of K values is 0 to 1, with the range 0.2 to 0.6 being most common.

Each soil mapping unit was assigned a K value from i) published soil survey reports of Glenn (Begg, 1968), Colusa (Harradine, 1948) or Yolo (Andrews, 1972) counties, ii) other counties where the soils are found or iii) published SCS Form Fives. If K values were not available from these sources, they were calculated from published data using the Wischmeier et al. (1971) nomograph. If published K values or data were unavailable, K values were estimated from those of similar soils in the watershed.

Slope length and steepness are important variables in determining erosion potential and soil loss. As slope length increased, the L value and erosion increased. Similarly, as slope angle or steepness increased so did erosion. The formula for the calculation of L and S is given by Wischmeier and Smith as Equation (3); where

TABLE 2. SOURCES AND ESTIMATED LEVELS OF ERROR IN FACTOR EVALUATION FOR USLE "A" VALUE CALCULATIONS

Parameter	Source(s) of error	% error
A value	lack of rain gages-yearly differences in precipitation	±20-100%
K value	no field data for most soils	±25%
L value	measurement error	±10%
S value	not tested for 18% slopes, assumed straight slopes	±20%
C value	no data for most vegetation and crops in the area	-100%
P value	no data for erosion control practices in the area	+50%

+ indicates estimate may be too high.

- indicates estimate may be too low.

± indicates estimate may be either too high or too low.

$$LS = (\lambda/72.6)^m \, (65.41 \sin^2\theta + 4.56 \sin\theta + 0.065) \qquad (3)$$

λ is slope length, m is an exponent which changes depending on slope steepness, and θ is the slope angle in degrees. Slope angle in percent can also be used with modification of the formula. We assumed straight slopes and used the m values suggested by Wischmeier and Smith (1978) of m = 0.5 for slopes over 5 percent, 0.4 for slopes of 3.5 to 4.5 percent, 0.3 on slopes of 1 to 3 percent, and 0.2 on slopes less than 1 percent. We determined slope length by averaging the distances between equally spaced topographic lines within soil mapping units. We made approximately 10 measurements per soil mapping unit in steep areas and five measurements of slope length in level areas. Slope percent was taken as the midpoint in the slope class of the soil mapping unit.

A main source of error in estimating the LS factor was that Equation 3 had not been tested for slopes over 18 percent and much of the watershed area was on slopes greater than 18 percent. Second, we assumed straight slopes, and some of the slopes we know are concave or convex. Finally, we assumed some error in the measurement of slope length, although we do not have a good measure of the size of this error.

The C value will vary depending on the season of the year, the crop or cropping sequence, or the land use if uncropped. Typical crop rotations as reported in Wischmeier and Smith (1978) do not occur in the Colusa Basin. In addition, current information on acreage of specific crops by soil type was not available.

Assumptions were made in order to develop C values based on discussions with SCS professionals and Cooperative Extension farm advisors. First, it was assumed that the western portion of the watershed which is uncropped has good, nearly continuous, cover during the winter period when the R value is high. During the months of November through March, the grass cover in these areas is growing and providing cover. The brush species also provide fairly effective cover even in those cases where they lose leaves and are dormant in the winter. Often this brush cover is found in thick stands.

Previous studies (Singer et al., 1976, 1980) at the Sierra Field Station near Marysville, California, have shown that a thick cover of ungrazed native annual grass reduced soil loss to nearly zero. A C-value of 0.001 was not unreasonable for such cover. We recognized that most of the upper areas in the CBD watersheds were grazed and that a cover factor of 0.001 may be too low.

The intermediate elevations between the permanent grazing areas and the cultivated croplands is used for dryland grain and grazing. Most of the watersheds do not have substantial acreages in fallow condition during periods of high R values. Thus, we assumed a C value of 0.001 for these areas. This is likely to be too low.

In the cropland during any one winter, some areas are left bare and the C value could be assumed to be 1. Over the long term, any one field will have some form of cover (i.e., sugar beets or stubble) in most years. For this analysis we assumed good continuous cover for cropland and selected C = 0.03 for this area.

We assumed that 60 percent of the basin was either rangeland or dry farmed and 40 percent was in cropland. Thus, the weighted average C value for the whole basin was 0.012 (0.6 x 0.001 + 0.4 x 0.03). This is a conservative (i.e., low) value of C.

Detailed results of these calculations are reported in Tanji et al., 1980a. Table 1 summarizes the soil loss calculated for the 24 watersheds in the basin. Seventeen soil series are found on slopes such that the calculated soil loss is in excess of 1 ton/acre (Table 3). The 102 soil mapping units comprised of these series can potentially contribute over 130,000 tons of sediment to the drain. This is over 48 percent of the total projected sediment production for the basin. It occurs on slightly more than 84,000 acres or approximately 8 percent of the land area. Steep slope is the characteristic shared by these 102 mapping units.

These projected erosion rates and soil losses are for the rainy winter season and do not include soil losses from irrigation which is considered in other parts of this report.

TABLE 3. SOIL SERIES THAT CONTRIBUTE TO MAPPING UNITS WITH POTENTIAL SOIL LOSSES IN EXCESS OF 1 TON/ACRE

Soil series name	Watersheds where mapping units are found	Total area occupied by phases§ (acres)	Soil loss (tons)	Proportion of total basin§§ area	
				area	soil loss
				(%)	
Altamont	1-4, 19	7,933	10,205	0.7	3.8
Ayar	2, 6	800	890	0.1	0.3
Balcom	7, 9-14, 16	12,049	19,061	1.1	7.1
Contra Costa	1-4	10,171	12,153	1.0	4.5
Corning	14	192	270	<0.1	0.1
Dibble	7, 9, 10, 12	5,188	10,271	0.5	3.8
Forgeus	6	40	40	<0.1	<0.1
Los Osos	2, 3, 4	1,039	1,154	0.1	0.4
Masterson	1	124	178	<0.1	0.1
Millsholm	1, 2, 3, 10, 12	16,113	27,499	1.5	10.2
Nacimiento	1, 2, 3	3,945	5,918	0.4	2.2
Neuns	1	24	28	<0.1	<0.1
Newville	1	7,392	13,208	0.7	4.9
Positas	7, 9-12	7,152	11,468	0.7	4.3
Rumsey	6, 7	2,929	3,092	0.3	1.1
Sehorn	1-3, 10-16	8,884	14,712	0.8	5.5
Shedd	1	54	71	<0.1	<0.1
TOTAL		84,029	130,218	8.0	48.4

§ Series are assumed to be equally represented in complexes.

§§ Watershed area 1,052,531 acres

Estimated soil loss 268,924 tons

Potential soil loss from the low slope cultivated areas is small on a per acre basis because of the low intensity rainfall, vegetative cover, and low slope angles. In the cultivated areas during the irrigation season average soil loss rates are similar to rates from high slope noncultivated areas during the rainy season in some years (Table 4).

Detailed best management practices for these two areas are considered in another section of this report.

COLUSA BASIN DRAINAGE AREA OUTFLOW

The outflow sampling station selected for the one-million-acre study area is CBD-1. It is located where a bridge extends Road 99E over CBD to meet Road 108, about 3.5 miles upstream from the outfall gates. From October

TABLE 4. IRRIGATION AND NONIRRIGATION SEASON SOIL LOSSES AT CBD-1 FOR FOUR YEARS

Year	Irrigation	Nonirrigation	Total
	Tons		
1978	53,970	>451,920	>505,890
1979	39,520	116,004	155,520
1980	54,800	290,120	344,920
1981	42,643	63,566	106,209

1977 through September 1981, CBD-1 was sampled weekly for suspended matter (turbidity and suspended solids) and salinity (electrical conductivity and total dissolved solids). Weekly water flow measurements by the velocity-surface area method were also conducted. In this method the instantaneous rate of flow was determined as the product of the cross-sectional area of the flowing water and the average velocity. All available data on water flow, suspended matter, and salinity were reported in the four annual reports to EPA (Tanji et al., 1978, 1980a, 1980b, 1981).

Precipitation

Precipitation gaging stations within the project area are located at Willows, the Sacramento National Wildlife Refuge (six miles south of Willows), Williams, and Dunnigan. Table 5 presents monthly precipitation from October 1977 through September 1981 for the Sacramento National Wildlife Refuge, Williams, and Dunnigan sites. The total precipitation during this period and the monthly precipitation were similar for the three valley floor stations. The heaviest rainfall was recorded in the month of January, except for the 1980 study period when precipitation was maximum in the month of December. Figure 3 contains a plot of the monthly precipitation from October 1977 through September 1981 for the Sacramento National Wildlife Refuge. The mean annual precipitation for the Colusa Basin Drainage Area was 20 inches for the period covering four years of study.

Water Discharge and Sediment Yield

Water discharge and sediment yield were monitored for the nonirrigation and irrigation seasons along CBD. The nonirrigation season was considered to be from October through April, and the irrigation season, March through September. During the nonirrigation seasons for the four years of study, 2,583,810 ac-ft of storm water with 925,730 tons of suspended matter was discharged from the study area. This measured channel discharge from CBD-1 was equivalent to 31 surface inches of precipitation runoff for four years. The sediment yield was equivalent to 1850 lbs/ac for four years in the one-million-acre drainage area. The comparison of water and sediment discharge for the four-year study period indicated that water and sediment discharge were greater in 1978 and 1980 than in 1979 and 1981. This was due to greater precipitation in 1978 and in 1980. The water discharged for 1978 and 1980

TABLE 5. MONTHLY PRECIPITATION IN COLUSA BASIN DRAINAGE AREA FROM OCTOBER 1977 THROUGH SEPTEMBER 1981 (INCHES)

Stations	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Total
Sacramento National Wildlife Refuge	1977-78	0.26	1.89	3.26	9.01	4.60	3.66	1.84	Tr	0.0	0.0	0.0	0.0	24.52
	1978-79	0.0	1.04	0.50	2.51	0.91	1.23	1.48	0.03	0.0	0.0	0.0	0.45	8.15
	1979-80	0.78	4.17	4.92	3.36	6.46	1.69	0.31	0.23	1.20	0.01	0.0	0.15	23.28
	1980-81	0.16	0.0	3.20	3.44	0.57	3.47	0.96	0.26	0.0	0.0	0.0	0.66	12.72
Williams	1977-78	0.37	1.90	2.72	8.28	3.83	2.83	1.42	0.0	0.0	0.0	0.0	0.0	21.35
	1978-79	0.0	1.67	0.53	5.00	3.90	1.37	1.63	0.05	0.0	0.0	0.0	0.15	14.30
	1979-80	1.16	3.51	4.48	3.17	5.99	2.09	0.37	0.17	0.13	0.05	0.0	0.0	21.12
	1980-81	0.13	0.31	1.88	4.07	1.20	2.80	0.53	0.19	0.0	0.0	0.0	0.88	11.99
Dunnigan	1977-78	0.25	2.74	3.09	9.11	3.63	3.66	1.48	0.10	0.0	0.0	0.0	0.0	24.06
	1978-79	0.0	1.89	0.58	6.08	5.36	1.82	1.84	0.04	0.0	0.0	0.17	0.05	17.83
	1979-80	1.15	2.17	5.09	3.22	9.36	1.86	0.96	0.19	0.06	0.01	Tr	0.0	24.07
	1980-81	0.26	0.18	3.67	5.30	1.06	2.90	0.72	0.16	0.0	0.0	0.0	0.55	14.80

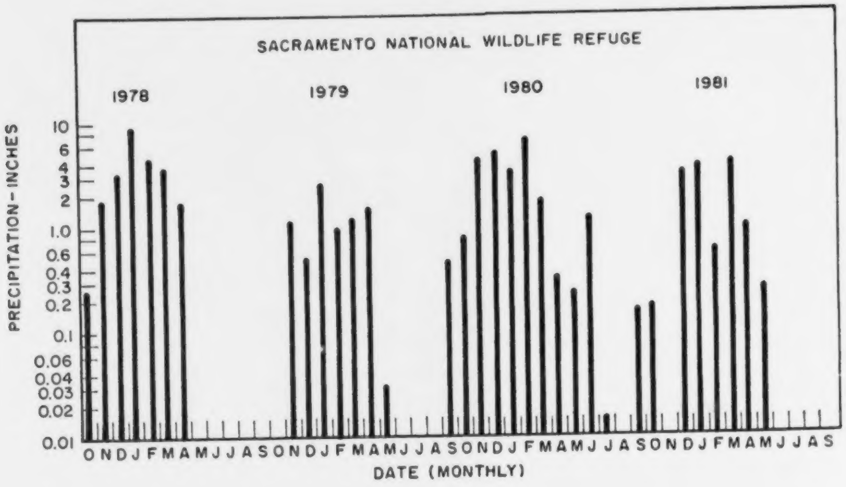


Figure 3. Monthly precipitation at the Sacramento National Wildlife Refuge from October 1977 through September 1981.

was nearly similar but the sediment discharged in 1978 was nearly twice that in 1980. This was due to the two-year period of drought followed by a wet year in 1978, and by the overgrazing of the pastured area in the watershed by sheep and cattle. The peak flow for 1980 was 21,620 ac-ft of water per day and suspended sediment concentration was 175 mg/ℓ. The peak flow in 1978 was 17,380 ac-ft of water per day and suspended sediment was 1,180 mg/ℓ.

During the irrigation seasons in the study period covering four years, 1,522,360 ac-ft of water and 190,930 tons of suspended matter were discharged from the Colusa Basin Drainage Area. This discharge for four years was equivalent to an average of 55 surface inches of return flow, and 1,100 lbs/ac of sediment based on a 1970 irrigation crop acreage of 346,900 acres. The sediment discharge and water flow were greater during the irrigation season of 1980 than any other year in the study period. In general, the suspended matter produced from the irrigated lands, mainly rice, were higher in May and September due to the large quantity of water discharged.

Suspended matter in water samples were determined gravimetrically (suspended solids) and optically (turbidity). The mass of suspended sediment was calculated by taking the product of concentration of suspended solids and volume of water. Table 6 summarizes the monthly and yearly discharges of water and suspended sediment at the CBD-1 outflow station.

TABLE 6. MONTHLY WATER FLOWS AND SUSPENDED SOLIDS AT CBD-1 1977-1981

Nonirrigation season				Irrigation season			
Month	Year	Flow (ac-ft)	SS (tons)	Month	Year	Flow (ac-ft)	SS (tons)
October	1977	-	-	April	1978	85,933	8,617
	1978	17,958	2,039		1979	51,608	2,847
	1979	33,203	2,999		1980	41,788	7,530
	1980	35,553	3,305		1981	52,359	7,468
November	1977	11,666	1,256	May	1978	58,320	8,140
	1978	22,457	1,566		1979	39,790	3,730
	1979	55,630	4,964		1980	71,610	14,233
	1980	35,137	3,291		1981	49,579	4,504
December	1977	22,735	1,728	June	1978	35,089	3,437
	1978	24,456	712		1979	30,065	1,592
	1979	72,212	41,531		1980	50,580	3,935
	1980	44,302	1,990		1981	50,990	3,147
January	1978	334,932	279,608	July	1978	44,365	3,310
	1979	98,311	17,891		1979	55,693	2,998
	1980	194,736	45,008		1980	68,016	2,464
	1981	60,369	24,917		1981	66,792	4,032
February	1978	311,016	116,715	August	1978	75,362	11,799
	1979	156,101	61,697		1979	75,770	9,476
	1980	300,924	140,228		1980	100,342	10,170
	1981	140,408	35,321		1981	76,009	9,359
March	1978	179,752	52,612	September	1978	77,230	18,663
	1979	75,176	12,904		1979	109,663	21,152
	1980	289,480	61,858		1980	91,869	16,466
	1981	67,293	11,590		1981	63,537	14,131
TOTAL	1978	860,100	451,919		1978	376,299	53,966
	1979	394,459	96,809		1979	362,589	39,520
	1980	946,185	296,588		1980	424,205	54,798
	1981	383,062	80,414		1981	359,266	42,644

Sediment Discharge and Hydrograph

Sediment discharge and hydrograph were developed for several stations along the CBD. Figure 4 gives the weekly sediment discharge and hydrograph for the outflow station (CBD-1) from October 11, 1977, through September 30, 1981. Flow measurements are shown to range from 175 cfs in mid October 1977 to a peak 10,900 cfs during the storm period in February 1980. The suspended sediment (SS) ranged from 10 to 1,455 mg/ℓ. The water discharge for the irrigation seasons ranged from 300 cfs in mid June to about 5,000 cfs in September, and the SS ranged from 20 to 260 mg/ℓ. The peak flow for the irrigation season corresponded to flood waters being drained from the rice fields prior to harvest.

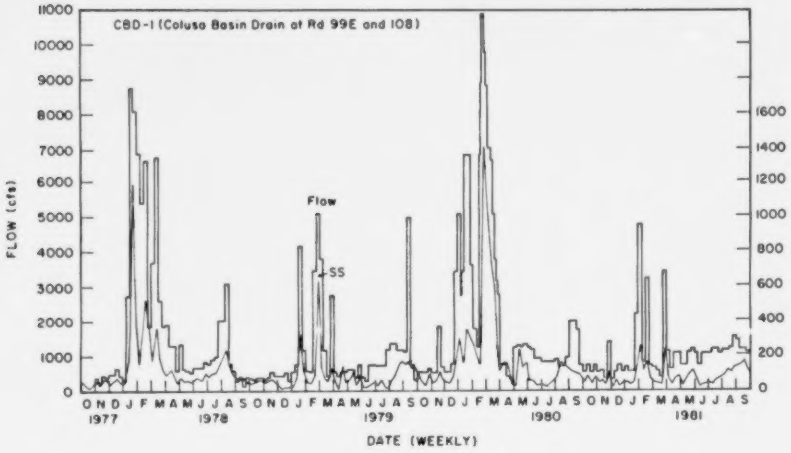


Figure 4. Measured flow and suspended solids concentration in weekly intervals in the outflow station CBD-1 near Knights Landing.

The sediment discharge and hydrograph showed that the flow rate and sediment concentration increased or decreased simultaneously. The magnitude to which the sediment discharge changed simultaneously with water discharge was different for the irrigation season than for the nonirrigation season. During the nonirrigation season the fine sediment fractions that form the washload of a stream, originating from sheet and rill erosion, were readily entrained in runoff. The greater the runoff the higher the sediment discharge. During the irrigation season a large quantity of water with low sediment concentration drained from the rice fields and diluted the suspended sediment concentration.

Plots of the sediment discharge and hydrograph for all other stations along the CBD are found in the annual reports (Tanji et al., 1978, 1980a, 1980b, 1981). In general, all plots showed that the stream sediment concentration increased slowly with an increased runoff rate and vice versa for runoffs of low intensities, and rapidly for runoffs of high intensities.

Sediment Rating Curves

Sediment rating curves were established from weekly measured sediment and water discharge at the outflow station (CBD-1). The rating curves are indicators for total sediments (wash load and suspended load) discharged from the one-million-acre study area. Figure 5 shows the sediment rating curve for CBD-1 which is a log-log plot of suspended sediment and flow rate for the study period. The suspended sediment shown was sampled with a suspended sampler and measured gravimetrically. The sediment discharge in Figure 5 was obtained from the product of the measured concentration and the volume of water discharged. The data was averaged weekly but no simple relationship appears to exist between sediment and water discharge. Figure 5 shows scattered points. This is due to the suspended sediment values resulting from a nonuniform and spatially-varied surface runoffs, or the given flow rates are the result of different hydrologic events. The water discharged resulted from the runoffs of different rainfall intensities and durations, and from the watershed with various soil texture, structure, vegetation, and soil slopes (steep and mild). It was also affected from surface runoffs from irrigated fields in the summer or from wastewater discharged from the urban areas. A different suspended sediment load would be expected to be found for each case. For example, a discharge of about 5,000 cfs in the irrigation season had a sediment concentration of 160 mg/ℓ while a similar discharge in a nonirrigation season had a sediment concentration of 290 mg/ℓ. The mean

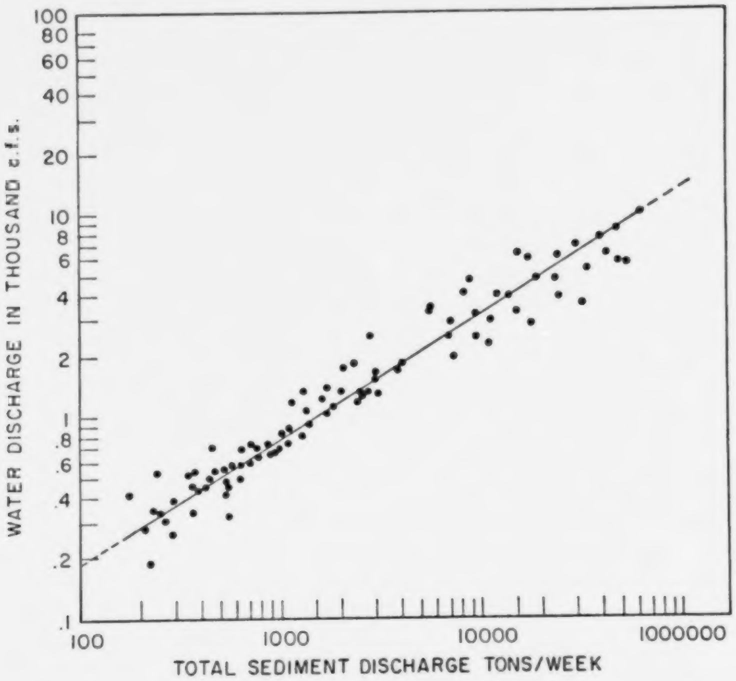


Figure 5. Sediment rating curve for outflow station (CBD-1) 1977 to 1978.

monthly sediment rating curves were established for the irrigation and nonirrigation seasons to obtain a better estimate of sediment discharge for a given water discharge from the study area. Figure 6 shows the sediment rating curves for the outflow station (CBD-1). In Figure 6, the curve for the irrigation season presents suspended sediment and water discharge from May through September while the curve for the nonirrigation season presents

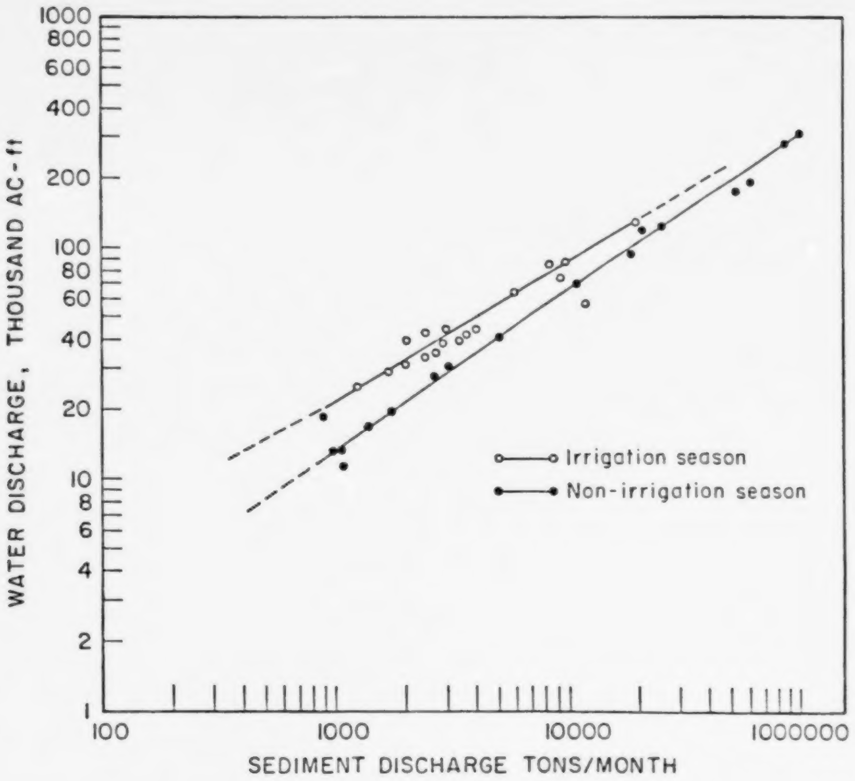


Figure 6. Sediment rating curve for outflow station (CBD-1) 1977-1980.

data from October through March. Both curves have different slopes as they approach low as well as high discharges. These rating curves can be approximated by a power relation of the form $Sd = KQ^n$ where Sd is the sediment discharge, Q is the water discharge, K is the intercept indicative of the relative erodibility, and n is the slope of the curve. It is necessary to extrapolate the curves to obtain the value of K. These rating curves may provide fairly satisfactory results for the prediction of mean monthly sediment discharge from the Colusa Basin Drainage Area.

Functional Relationships

Functional relationships for suspended sediment and its physical factors (current velocity, flow rate, water depth, turbidity) were obtained using weekly measurements of current velocity, water depth, and turbidity. The data on these parameters were analyzed by the simple regression method. A least squares fit to the data resulted in several functional relations between suspended sediment and the related parameters, but the exponential relation was the best fit to the available data. Figure 7 and 8 show that suspended sediment in CBD-1 is exponentially related to the current velocity and flow rate. These types of functional relations existed for suspended sediment for three consecutive years, 1978 to 1980. In the 1981 data, the suspended sediment was linearly related to current velocity and flow rate. This may be due to the different flow rate, and the mechanism of erosion. At flow rates less than 5,000 cfs, the erosion of the bed material or soil

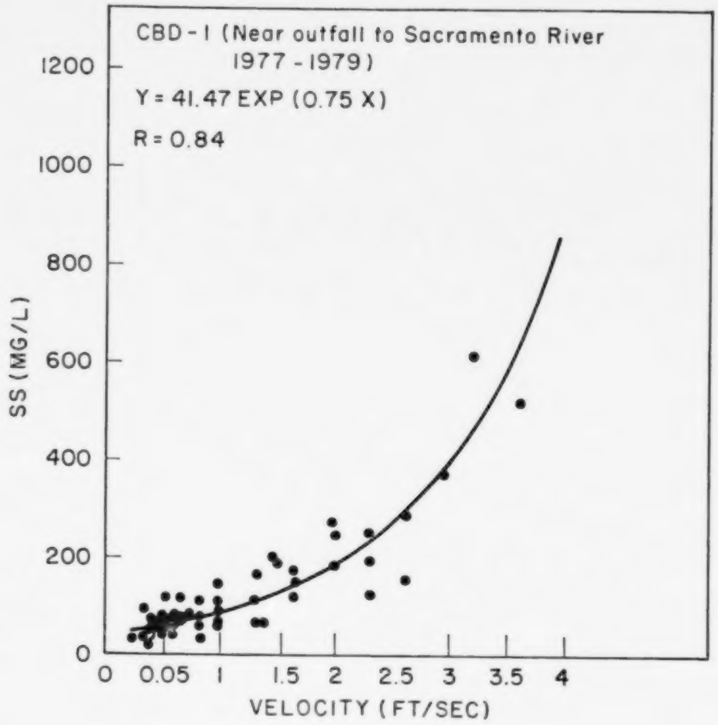


Figure 7. Relation between suspended sediment in mg/liter and velocity in fps at CBD-1.

surface occurred particle by particle and aggregate by aggregate. A massive erosion of the bed material or soil surface occurred at a flow rate greater than 5,000 cfs. The linear relation between suspended sediment and flow rate changed to an exponential one when flow rate exceeded 5,000 cfs. In addition to the functional relations between sediment and current velocities and flow rate, attempts were made to correlate turbidity with suspended sediment.

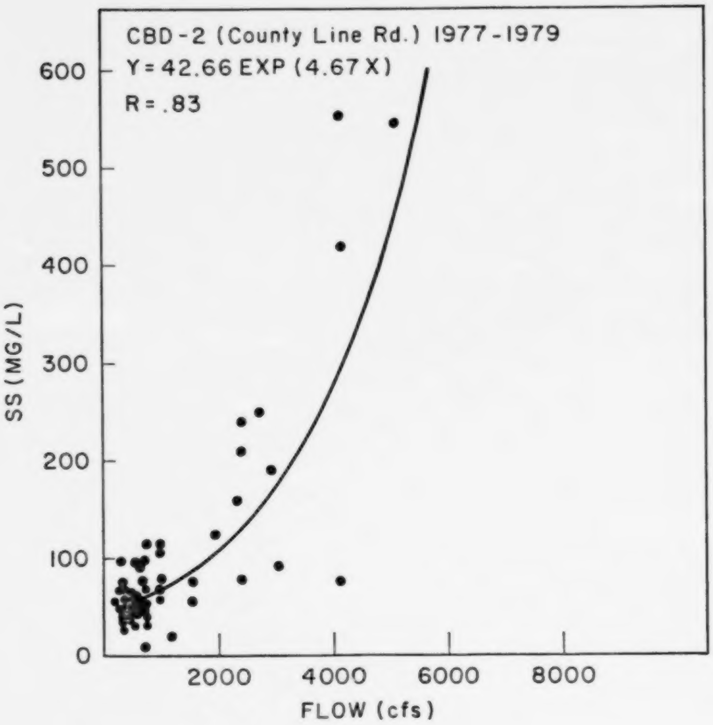


Figure 8. Relation between suspended sediment in mg/liter and flow rate in fps at CBD-1.

Figure 9 shows that turbidity in CBD-1 is linearly related to suspended sediment with a correlation coefficient (R^2) of 0.98. Such functional relations were developed for all other stations along the CBD (Tanji et al., 1978, 1980a, 1980b, 1981). These relationships showed different but high values of R^2, with coefficients remarkably uniform in the functional equations.

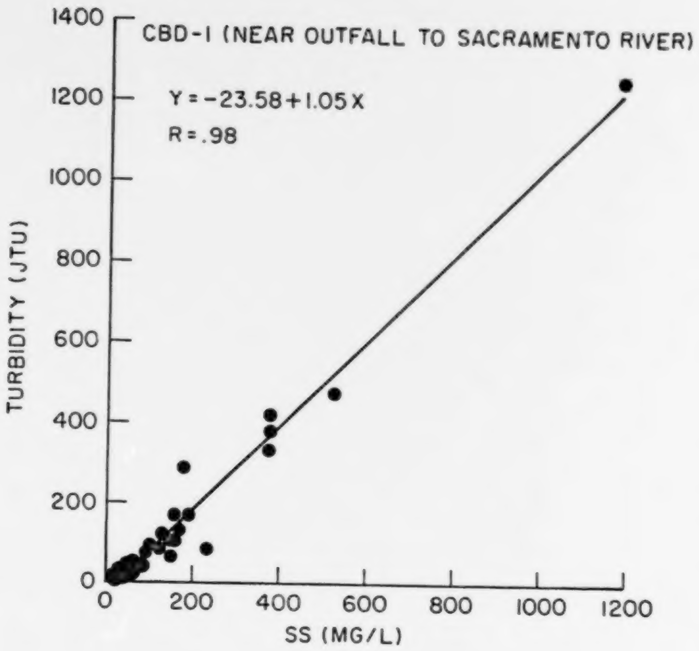


Figure 9. Relation between turbidity in Jackson Turbidity Units and suspended solids in mg/liter at CBD-1.

COLUSA BASIN DRAIN OUTFALL PLUME IN SACRAMENTO RIVER

A turbid plume originating at the CBD outfall at Knights Landing was studied to determined the effects of CBD water on Sacramento River water. The turbid water from CBD that discharges into the Sacramento River forms a plume downriver at the mouth of CBD along the left bank of the Sacramento River. It spreads across the river as the drain and river waters become mixed. The river and drain waters are assumed to be completely mixed at 1,900 meters downriver (Ford et al., 1980).

Nine stations were selected to monitor turbidity, EC, color, and chlorophyll-a. Seven sampling stations were established in the Sacramento River across the Bascule Bridge, about 200 meters downriver from the mouth of CBD. The other two stations were located in the drain (Station 2) and a few meters upriver (Station 1). Figure 10 shows the location of the nine stations and a plume boundary. This study was conducted biweekly from May through September 1981.

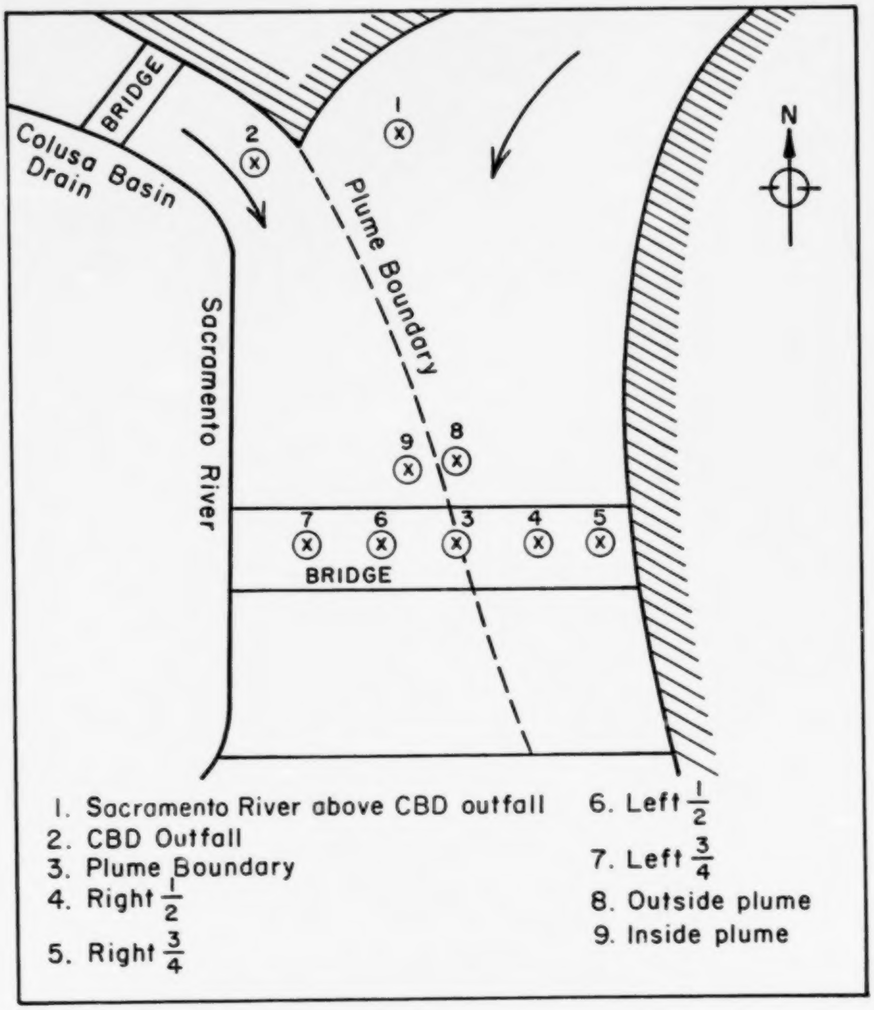

BRIDGE
Colusa Basin Drain
Sacramento River
Plume Boundary
BRIDGE
N
1
2
3
4
5
6
7
8
9
1. Sacramento River above CBD outfall
2. CBD Outfall
3. Plume Boundary
4. Right 1/2
5. Right 3/4
6. Left 1/2
7. Left 3/4
8. Outside plume
9. Inside plume

Figure 10. Locations of the sampling stations in the Sacramento River.

The data on quality parameters and the visual observation indicated that the discharge of water from CBD altered the quality of the Sacramento River water. Three quality parameters are plotted against the plume width. Figure 11 shows the turbidity profile of mixed Sacramento River and CBD waters at seven stations across Bascule Bridge. The turbidity of the Sacramento River water upriver (Station 1) varied from 7 to 15 JTU with an average of 10 JTU. The turbidity of CBD water in the drain outfall varied from 15 to 82 JTU with an average of 50 JTU. The turbidity of the mixed Sacramento River and CBD waters at the plume boundary (Station 3) averaged at 24 JTU. This average value may drop to as low as 15 JTU when the CBD water is fully mixed with the Sacramento River water. In general, as the turbid CBD water mixed with the river water, the suspended particles diffused into the river water. Figure 11 shows that turbidity decreased almost exponentially across the plume width. Each graph in Figure 11 contains three distinct points designated A, B, and C. Point A is the CBD outfall, B is at the plume boundary, and C is the Sacramento River water not affected by the CBD water. The turbidity graph of Figure 11 followed the same pattern from May through September with the exception of June 9. The gate releasing the CBD discharge into the Sacramento River on June 9 appeared closed, and the CBD discharge was extremely low. Turbidity of the mixed water was high in late May and September as discharges from CBD were increased into the river.

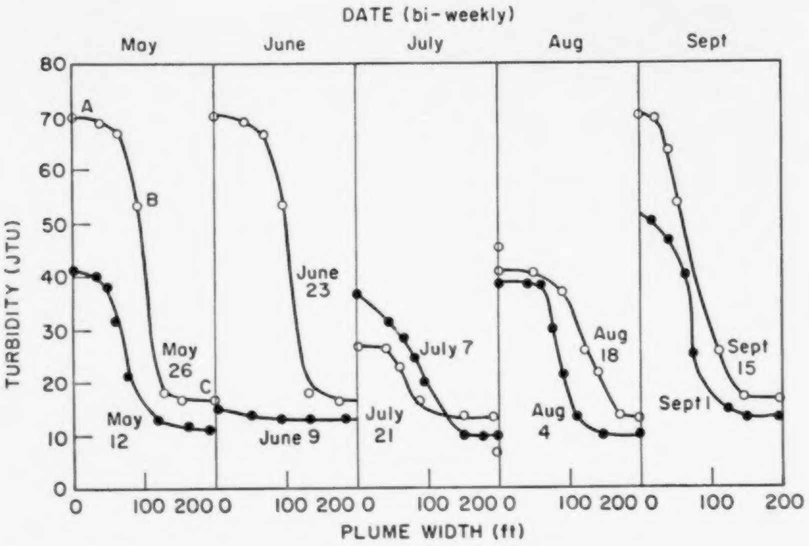


Figure 11. Turbidity profile for a mixture of CBD and Sacramento River waters.

The CBD discharge water changed the salinity of the Sacramento River water in terms of specific conductance (EC). The EC of upriver water ranged from 150 to 210 µmhos/cm with an average of 170 µmhos/cm. The EC for the drain water ranged from 460 to 730 µmhos/cm with an average of 570 µmhos/cm.

The EC of the mixed CBD and Sacramento River waters in the plume boundary (Station 3) ranged from 180 to 510 µmhos/cm with an average of 270 µmhos/cm for the study period. The average EC of the mixed water as compared to the upriver water was raised from 170 to 270 µmhos/cm but the water was not fully mixed at the bridge. According to Ford (1980), the EC averaged 200 µmhos/cm 1,900 meters downriver from the mouth of CBD when the salinity averaged 145 µmhos/cm at upriver and 640 µmhos/cm at the drain. For our study period the average salinity of the fully mixed water is estimated to be 220 µmhos/cm. Assuming similar flows, this means the CBD discharge may have changed the EC of the Sacramento River water by about 20 percent. Figure 12 shows the salinity profile for the partially mixed water at seven stations across Bascule Bridge. Point A in Figure 12 represents EC for the CBD outfall water, point B represents EC at the plume boundary, and point C is EC of the river water not affected by the CBD discharge. The EC was highest in late May and lowest in late September. In May the rice fields were drained for the first time following application of herbicides and fertilizers. The first drain water from the rice fields contained readily leachable salts. The EC dropped gradually as the drainage from the rice fields continued (Figure 12). The salinity was lowest in September due to the dilution effect.

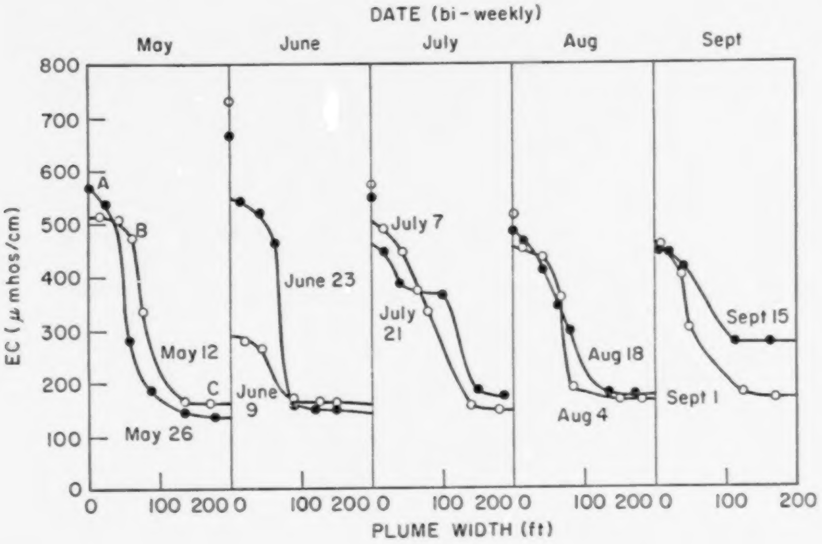


Figure 12. Salinity profile for a mixture of CBD and Sacramento River waters.

Color in water is generally caused by the presence of metallic ions, humus, peat materials, weeds, plankton, and industrial wastes. Color is removed to make water suitable for general and industrial use. The methods available to determine color are either visual or instrumental. The visual platinum cobalt method, applicable to samples of potable water, was selected for this study. The term color used in this report is true color, color of the water caused by dissolved organic matter.

The color of the Sacramento River water changes with the discharge of the CBD water. The color of upriver water averaged 10 chloroplanate units (CPU). The color of the mixed water at plume boundary (Station 3) ranged from 10 to 20 CPU with an average of 15 CPU. The average color of the drain water was 25 CPU. The discharge of the CBD water changed the color of the Sacramento River water. Figure 13 shows the color profile of the mixed water. The color changed exponentially with plume width as the CBD water mixed with the river water. There was an increase in the color profile of the mixed water from May through September. The maximum color change in late September corresponded to the increased water discharged from the rice fields, water containing high concentrations of suspended organic matter.

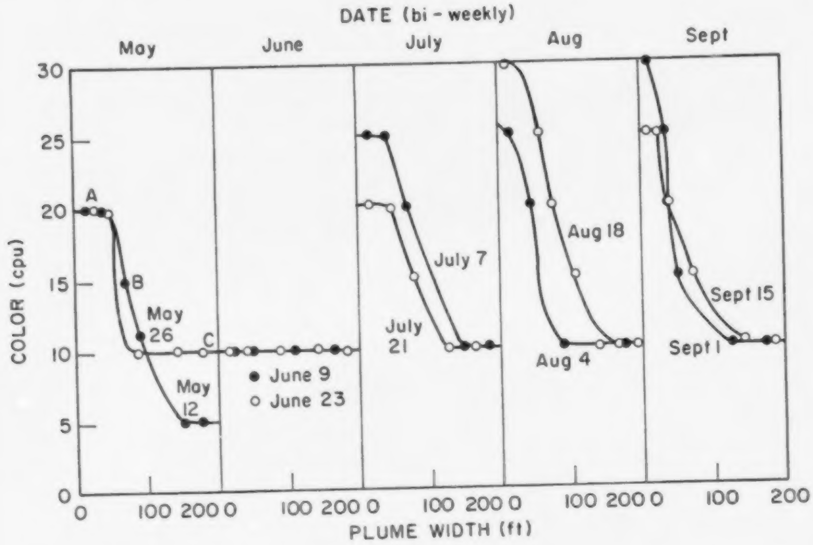


Figure 13. Color profile for a mixture of CBD and Sacramento River waters.

Color intensity generally increased with increasing turbidity and pH. A simple regression analysis was performed to the color and turbidity, and color and pH data. A least squares fit to the turbidity and color data showed that color changed linearly with turbidity. The correlation coefficient (R^2) for this analysis was 0.94. There was a linear function between color and pH with R^2 of 0.82. The color changed with pH due to changes of suspended organic particles. Colloidal organic particles have pH-dependent charges which at acidic pH levels decomposes to fulvic acid which contains low color intensity. In alkaline pH, the carboxyl group (R-COOH) of organic particles release H^+ and become negatively charged (R-COO$^-$), reacting with ions such as iron to produce humate compounds containing high color intensity. As the pH changed, the fulvic compound changed to humic compound which changed the color intensity.

The algal biomass of the CBD outfall, mixture of CBD and Sacramento River waters, and the Sacramento River above the CBD outfall were determined by measuring chlorophyll-a. Pheophytin, a degradation product of chlorophyll-a, was also determined.

The algal biomass concentration ranged from 0.02 to 0.12 mg/ℓ for the upriver water with an average of 0.09 mg/ℓ. The average algal biomass for the CBD water was 0.05 mg/ℓ. The algal biomass for the river water above the outfall was higher than the CBD outfall due to more light availability. The pheophytin of the CBD outfall was higher than the river water due to high endogenous respiration rate for algae in the rice fields and CBD discharges. The concentration of pheophytin contributed to the increase in organic matter in the river water resulting in an increase in color intensity.

In addition to water quality parameters, the effect of CBD discharge on the bed sediment of the Sacramento River was studied. Samples of the bed materials were obtained with a Ponar dredge from beneath the water column at the Sacramento River below and above the CBD outfall. The sediment was dried and subjected to particle size analysis using the dry sieve method. The size distribution found in these samples are plotted as cumulative curves showing the frequency distribution of grain sizes. Figure 14 gives the particle size analysis of bed sediment above the CBD outfall (curve B) and below the outfall (curve A). The material was predominately gravel in the upstream sample while the downstream sample was mostly medium sand. The outfall of CBD into the Sacramento River appears to have a significant affect on the bed material of the river.

GLENN-COLUSA IRRIGATION DISTRICT

Glenn-Colusa Irrigation District (GCID) is the largest irrigation district in the Sacramento Valley. GCID delivers water to 120,000 to 140,000 acres of croplands which is more than one-third of the irrigated land in the Colusa Basin, and to 4,800 to 11,000 acres of refuge lands. Table 7 presents information and data over the past seven years, including the 1977 drought year.

In the irrigation seasons from 1978 through 1981, a total of 3,448,900 ac-ft of water was delivered to croplands (Table 7). Three-fourths of the croplands were in flooded rice culture, which ranged from 90,600 to about 105,900 acres each year.

Figure 15 contains a map of this 163,700 acre irrigation district, showing the main supply canal, drain laterals, and upper reaches of CBD. The supply water diverted from the Sacramento River and Stony Creek is conveyed by the 65 mile, 3,000 cfs capacity main canal that runs along the District's western boundaries. The District's 400 miles of laterals distribute water to

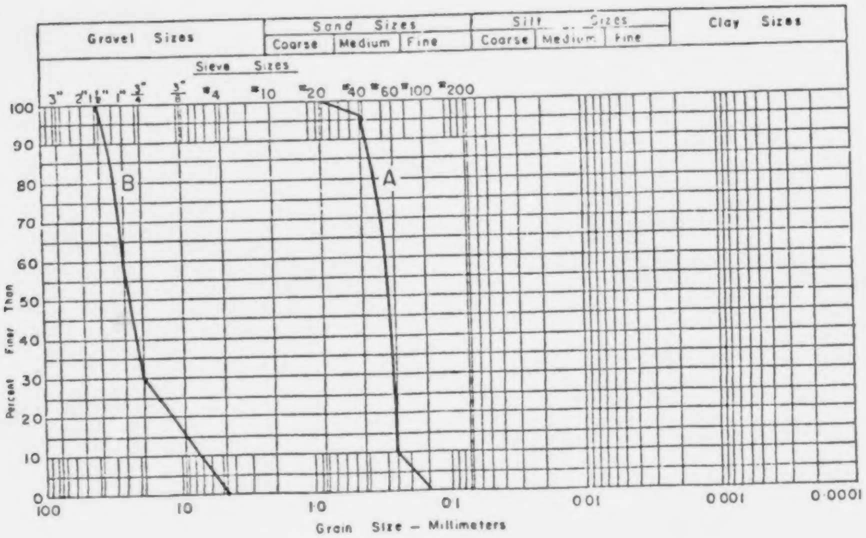


Figure 14. Size fraction analysis of channel bed samples in the Sacramento River above (curve B) and below (curve A) the outfall of Colusa Basin Drain, August 3, 1978.

western boundaries. The District's 400 miles of laterals distribute water to growers and the refuge lands. Rice is flooded throughout the growing season with continuous spill of water from the border levee checks. GCID usually captures about half of the drain waters for reuse by gravity diversions and drain pumps. It discharges the remaining half, about 20 to 30 percent of diversions, into the CBD (Drain 2047) through eleven lateral drains.

Flow of Water and Suspended Matter

Table 8 lists the GCID sampling stations and Figure 15 shows the location of these stations. GCID collected water samples, and estimated water flows for the 15 stations at monthly intervals, some stations at weekly to biweekly intervals. In all of the stations along CBD (Drain 2047) and its tributaries, the maximum and average concentrations of SS in the study period were higher in the nonirrigation season than in the irrigation season. The minimum concentration of SS for the irrigation and nonirrigation season were similar. Table 8 gives the maximum, minimum, and the average values of SS in mg/ℓ for the four-year study period. The maximum values of SS for the nonirrigation season represented the storm runoffs from late January to late March. The minimum values represented the runoffs from October to December. The maximum values of SS for the irrigation season were recorded in late April to May when flooded water depths in the rice fields were lowered. Detailed data on water flows, suspended matter, and salinity for these stations were reported in the annual report to EPA (Tanji et al., 1978, 1980a, 1980b, 1981).

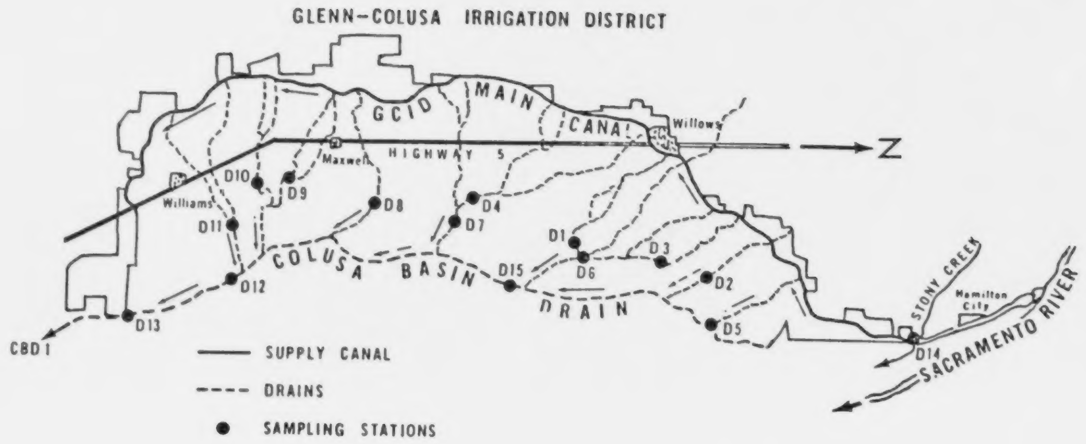

GLENN-COLUSA IRRIGATION DISTRICT
GCID MAIN CANAL
HIGHWAY 5
Willows
Maxwell
Williams
Z
D1
D2
D3
D4
D5
D6
D7
D8
D9
D10
D11
D12
D13
D14
D15
COLUSA BASIN DRAIN
CBD1
STONY CREEK
Hamilton City
SACRAMENTO RIVER
SUPPLY CANAL
DRAINS
SAMPLING STATIONS

Figure 15. Map of Glenn-Colusa Irrigation District.

TABLE 7. GLENN-COLUSA IRRIGATION DISTRICT (GCID) WATER USE DATA, 1975-80

Water use	1975	1976	1977	1978	1979	1980	1981
Irrigated Crops (ac)							
Rice	93,326	81,190	52,930	90,609	96,470	99,197	105,902
Tomatoes, Sugar beets	2,638	2,604	2,986	2,022	1,782	922	1,838
Clover, Alfalfa, Corn, Orchards	11,232	15,434	12,123	10,053	10,025	10,573	7,723
General Crops	6,293	15,466	9,958	11,136	10,193	7,660	9,463
1 & 2 Irrigations (wheat, barley, oats, etc.)	10,405	15,973	36,865	8,422	7,086	8,931	9,425
Duck Pond	2,392	2,733	2,328	3,023	3,378	3,575	3,641
Subtotal	126,286	133,400	117,190	125,265	128,934	130,858	138,262
Refuge (ac)	6,150	6,299	5,194	4,777	7,850	10,914	11,192
Total Acreage (ac)	132,436	140,234	122,384	130,042	136,784	141,772	11,192
Sacramento River Diversions (ac-ft)	711,300	835,300	668,400	695,500	784,600	718,500	882,600
Stony Creek Diversions (ac-ft)	124,100	30,700	0	105,500	67,100	117,700	77,400
Total Diversions (ac-ft)	835,400	866,000	668,400	801,000	851,700	836,200	960,000
Drain Outflow	243,500	183,800	132,400	252,400	212,400	262,400	268,800
Net Used (ac-ft)	591,900	682,200	536,000	548,600	639,300	609,800	666,300
% Leaving GCID (ac-ft)	29	21	20	32	25	31	29
Drain Recapture (ac-ft)	221,900	214,700	135,200	193,600	243,000	224,700	236,000
Lateral Spills (ac-ft)	34,300	13,900	24,600	26,400	28,400	25,900	20,200
Refuge Credit (ac-ft)	35,537	41,591	28,988	49,544	45,310	62,370	66,981

TABLE 8. GLENN-COLUSA IRRIGATION DISTRICT SUSPENDED SOLIDS DATA (MG/ℓ) FOR THE IRRIGATION AND NONIRRIGATION SEASONS 1977-1981

Sampling station	Station No.	Nonirrigation season Max	Nonirrigation season Min	Nonirrigation season Avg	Irrigation season Max	Irrigation season Min	Irrigation season Avg
Main supply canal	D14	697	2	93	81	4	22
Bondurant Slough	D2	497	1	61	34	1	12
Drain 55	D3	523	2	35	256	2	15
Salmon Hole	D1	1,500	3	149	82	5	21
Willow Creek	D6	932	8	120	75	3	24
Logan Creek	D4	353	18	71	142	13	43
Hunter Creek	D7	730	16	118	73	9	36
Stone Corral Creek	D8	938	19	141	313	20	67
Kuhl Weir	D9	982	9	109	71	5	30
Section 25	D10	459	6	111	200	9	50
Freshwater Creek	D11	788	9	128	236	20	106
Drain 2047 @ Sidds Rd	D5	356	2	38	77	1	21
Drain 2047 @ Princeton Rd	D15	324	1	73	79	8	28
Drain 2047 @ Davis Weir	D13	1,006	8	135	219	6	58

Table 9 presents a summary of the water and SS discharged within GCID during the irrigation season for the four years of study. For the April through September period in four years, GCID diverted a total of 3,115,310 ac-ft of supply water containing 69,090 tons of SS from the main canal (D-14). During the same period, GCID discharged 817,940 ac-ft of water containing 75,930 tons of SS. These inflow-outflow data indicate that 26 percent of diverted water and 110 percent of SS load were discharged. Table 9 shows that Stone Corral Creek (Station 8) had both the highest SS load and water flow.

COLUSA BASIN DRAIN TRIBUTARIES

Sediment Production from Flood Runoff

Tributaries such as Stone Corral, Funks and Buckeye Creek were monitored at several stations during the 1977-8 study period. Stone Corral Creek at Sites Road, monitored in 1978, shows five runoff events exceeding an average daily flow of 10 cfs (Fig. 16). Figure 16 shows daily average, maximum, and minimum flows for the period January through April, 1978.

Table 10 gives measured suspended sediment (SS) and flow rate in Stone Corral Creek at McDermott Road, Stone Corral Creek at Frontage Road, Funks Creek at McDermott Road, and Lenahan Weir during the winter runoffs from 1978 through 1980. Funks Creek drains a watershed adjacent to Stone Corral Creek and joins the latter near Maxwell (Fig. 1). SS was low until January 10, 1978, when the SS concentrations abruptly increased with the

TABLE 9. TOTAL WATER FLOWS AND SS DURING THE 1978-81 IRRIGATION SEASONS IN GLENN-COLUSA IRRIGATION DISTRICT

Station	Year	Flow (ac-ft)	SS (tons)	Station	Year	Flow (ac-ft)	SS (tons)
Supply Canal							
D14	1978	771,551	23,208	D8	1978	32,496	2,788
	1979	664,988	19,412		1979	33,147	2,546
	1980	819,697	16,130		1980	32,450	3,600
	1981	859,070	10,340		1981	34,490	1,401
Drain Laterals							
D2	1978	8,813	138	D9	1978	18,226	886
	1979	-	-		1979	16,521	835
	1980	755	-		1980	11,937	350
	1981	9,030	81		1981	20,800	655
D3	1978	45,214	1,018	D10	1978	15,907	971
	1979	15,063	190		1979	15,655	774
	1980	12,794	140		1980	16,785	1,460
	1981	13,370	166		1981	20,390	514
D1	1978	9,045	380	D11	1978	15,694	1,785
	1979	2,131	510		1979	10,225	823
	1980	2,276	50		1980	19,427	4,060
	1981	1,860	43		1981	25,940	3,721
				Colusa Basin Drain			
D6	1978	18,846	939	D5	1978	18,189	400
	1979	18,986	559		1979	14,410	426
	1980	21,411	450		1980	15,677	370
	1981	17,280	352		1981	30,470	567
D4	1978	12,951	802	D15	1978	86,099	3,357
	1979	13,392	675		1979	34,703	1,398
	1980	16,720	810		1980	35,628	1,100
	1981	13,640	543		1981	40,270	1,762
D7	1978	16,837	821	D13	1978	191,105	18,693
	1979	22,082	753		1979	211,885	16,594
	1980	11,660	660		1980	240,871	19,300
	1981	17,990	511		1981	174,080	21,340

TABLE 10. SUSPENDED SEDIMENT (SS) AND FLOW DATA (Q) IN STONE CORRAL CREEK AND FUNKS CREEK DURING THE WINTER RUNOFFS

	Stone Corral Creek				Funks Creek			
	at McDermott Road		at Frontage Road		at McDermott Road		at Lenahan Weir	
Date	SS (mg/ℓ)	Q (cfs)	SS (mg/ℓ)	Q (cfs)	SS (mg/ℓ)	Q (cfs)	SS (mg/ℓ)	Q (cfs)
1/12/78	16,190	2,000	2,630	1,500	-	-	5,250	1,500
2/6/78	2,110	-	1,350	-	1,600	-	1,450	-
2/7/78	3,360	1,900	3,200	2,000	3,940	2,700	4,200	2,200
2/8/78	428	500	532	2,200	808	500	636	-
3/6/78	154	150	86	-	39	140	44	350
3/7/78	127	150	39	250	44	140	44	200
3/9/78	196	270	266	-	232	250	268	-
1/15/79	2,075	400	2,518	425	632	112	912	-
2/14/79	817	183	857	189	411	102	676	-
2/20/79	344	40	196	45	272	15	374	-
3/27/79	6,452	840	4,804	900	4,922	1,046	2,764	-
12/24/79	613	120	961	126	1,502	134	1,778	-
1/12/80	858	534	1,020	597	985	201	1,238	-
2/19/80	1,524	2,080	1,427	1,174	2,206	1,260	2,877	-
3/3/80	110	144	139	154	140	83	170	-

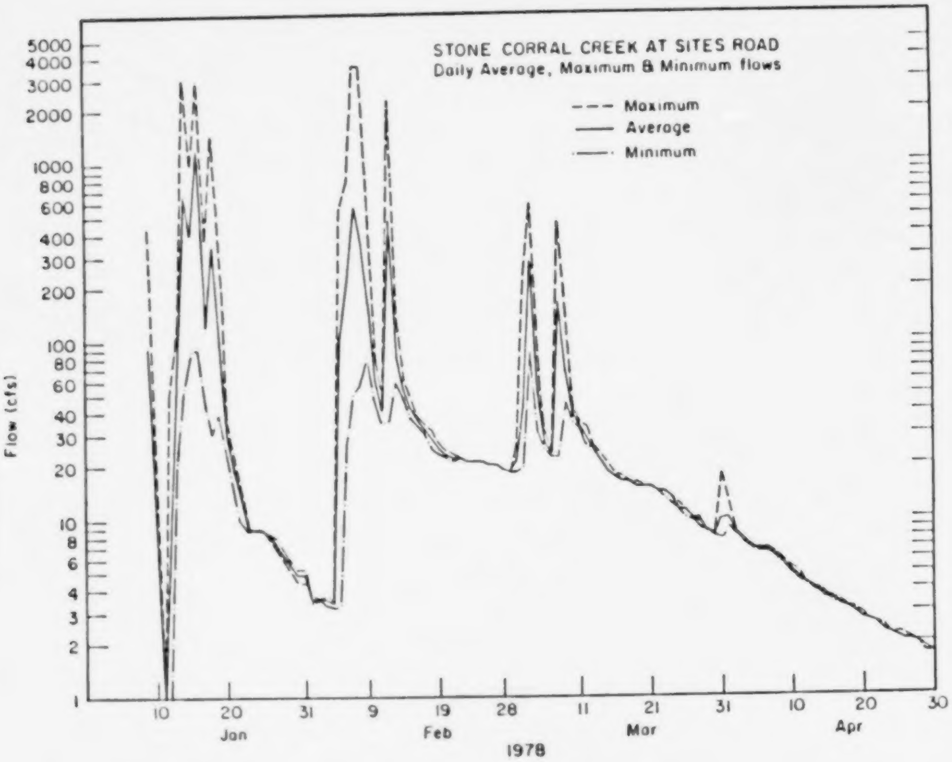


Figure 16. Daily instantaneous maximum and minimum flows and daily average flows in Stone Corral Creek at Sites Road from January through April 1978.

first storm runoff in two years. The heavy precipitation prior to or on January 16 produced flood flows up to 2,000 cfs, and SS up to 16,190 mg/ℓ. The next major storm in early February produced similar peak flows but less SS concentration. Peak flows of 1,900 cfs spilled over the banks with SS concentration of 3,360 mg/ℓ, five times less than the SS concentration of previous storms. This was due to the two year drought period as the fine sediment fractions that formed the washload of a stream were readily entrained in the runoff with the first storm. The third storm occurred in February 1980. Stone Corral Creek at McDermott Road recorded flows of 2,080 cfs with SS concentration of 1,525 mg/ℓ. It was estimated that over 87,400 tons of SS were produced on January 16 in Stone Corral Creek at McDermott Road.

Funks Creek at McDermott Road recorded three heavy storms during the study period. SS ranged from 40 to 4,920 mg/ℓ, and flood flows ranged from 85 to 3,700 cfs (Table 10). The sediment discharged from Funks Creek was less than Stone Corral Creek due to its smaller size.

Stone Corral and Funks Creeks were monitored weekly on a yearly basis for the entire study period (1977-1981). Weekly water flows, SS and water quality data were reported in EPA reports (Tanji et al., 1978, 1980a, 1980b, and 1981).

Table 11 gives flow (Q) and SS data for Buckeye Creek near Dunnigan. Buckeye Creek drains part of the Dunnigan Hills, the site of the SCS pilot sediment project and the location of the Dunnigan precipitation gaging station (Fig. 1). The first major storm runoff occurred on January 9, 1978, with flows estimated from 125 to 150 cfs and SS concentrations from 6,500 to 7,200 mg/ℓ. The second major storm on January 16 produced flood flows exceeding 1,500 cfs, and sediment concentrations of 10,500 and 15,700 mg/ℓ recorded at Road 2. During the 1979 and 1980 winter runoffs, several major storms occurred which produced flood runoffs up to 1,400 cfs and SS concentration up to 11,785 mg/ℓ. The sediment discharged from Buckeye Creek was less than Stone Corral Creek for each storm, due to its smaller drainage area.

Figure 17 presents data collected from intensive monitoring of Buckeye Creek at Roads 2 and 89 on February 12, 1978. The measured current velocity at Road 89 throughout this period was 4.6 fps (ft/sec). Figure 17 gives the hydrograph, SS, and the mass of SS discharged. During this five-hour period about 170 tons of SS were discharged at Road 2, and 400 tons at Road 89.

In addition to the established sampling stations during the storm runoff period, 15 creeks intersected by Interstate 5 were surveyed twice for SS, for SS, EC, and turbidity (Tanji et al., 1978). The SS concentration ranged from 145 mg/ℓ in Salt Creek to 1,750 mg/ℓ in Cache Creek. The sediment discharged from these creeks were less than Stone and Funks Creeks due to their smaller drainage area.

Sediment Production from In-Channel Erosion

A special field study was conducted in a three mile reach of Stone Corral Creek between Lovelace Weir and Four Mile Road (Fig. 18) to determine the in-channel erosion.

Seven sampling stations were selected along the drain. SS and water flows were measured weekly from May 2 to September 18, 1978. The results were reported in an annual report to EPA (Tanji et al., 1978). The data collected from the study were used to obtain a basic mass balance of SS and water flows. Mass emission of sediment by in-channel erosion (MID) was calculated by considering the mass of sediment discharged (M_o) from the system by outflow of water from the three mile reach of study area, the mass of sediment input to the system by flooded rice fields (M_r), the mass of sediment input by inflow of upstream water (M_i), and deposition (M_d) by process of flocculation and sedimentation. The mass balance equation is:

$$\mathrm{MID} = M_o - M_r + M_d + M_i \tag{4}$$

The input of SS and flows at Lovelace Weir were 62.8 tons and 1,960 ac-ft respectively. The output of SS and flows at Four Mile Road were 372.8 tons and 3,070 ac-ft, respectively. There was an increase of 31 tons of SS

TABLE 11. SUSPENDED SEDIMENT AND FLOW DATA IN BUCKEYE CREEK DURING THE WINTER RUNOFFS

	at Road 2		at Road 88		at Road 89	
Date	SS (mg/ℓ)	Q (cfs)	SS (mg/ℓ)	Q (cfs)	SS (mg/ℓ)	Q (cfs)
1/9/78	6,870	125	6,520	140	7,200	150
1/16/78	10,470	1,500	15,670	1,500	-	-
1/17/78	708	1,500	-	-	-	-
1/19/78	216	-	212	60	352	60
2/7/78	7,130	-	4,120	-	11,160	1,000
2/9/78	734	500	814	-	-	-
3/9/78	178	-	224	60	356	50
1/15/79	3,314	150	3,018	225	1,632	250
2/14/79	1,546	35	825	70	641	75
2/20/79	7,372	225	7,576	425	8,012	450
2/22/79	2,892	-	5,128	-	1,896	-
1/12/80	7,452	-	4,406	-	4,696	-
2/16/80	880	50	366	70	392	80
2/17/80	11,784	-	-	-	-	-
2/19/80	6,062	800	8,738	1,200	7,632	1,400
3/3/80	366	20	370	35	586	40

between the inflow and outflow stations. During the 12-day study period, 130 tons of SS were contributed by the 1,110 ac-ft of water drained from the surrounding rice fields, 10.4 tons of SS diverted by the 112 ac-ft of drain water captured at the Compton-Delevan Weir, and an estimated 41.6 tons of SS deposited upstream of the Compton-Delevan Weir due to reduced flow velocities. From the mass balance equation a calculated 190 tons of SS was produced from within this three mile reach of Stone Corral Creek. This in-channel source resulted mainly from resuspension of sediments deposited from the preceding winter storm runoffs.

SUPPORTING TECHNICAL RESEARCH

S and K Factors in the Universal Soil Loss Equation (USLE)

S factor analysis--

Slope steepness is a critical parameter in estimating potential soil losses from the western portion of the basin. We used an enlarged rainfall simulator (Tanji et al., 1980b) to evaluate the effect of slope on soil loss. The S factor, calculated by Eq. 5 for the USLE (Wischmeier and Smith, 1978), is the ratio of soil loss at any slope angle to soil loss at the standard 9 percent slope, and θ is the slope angle in degrees.

$$S = 65.41 \sin^2\theta + 4.56 \sin\theta + 0.065 \qquad (5)$$

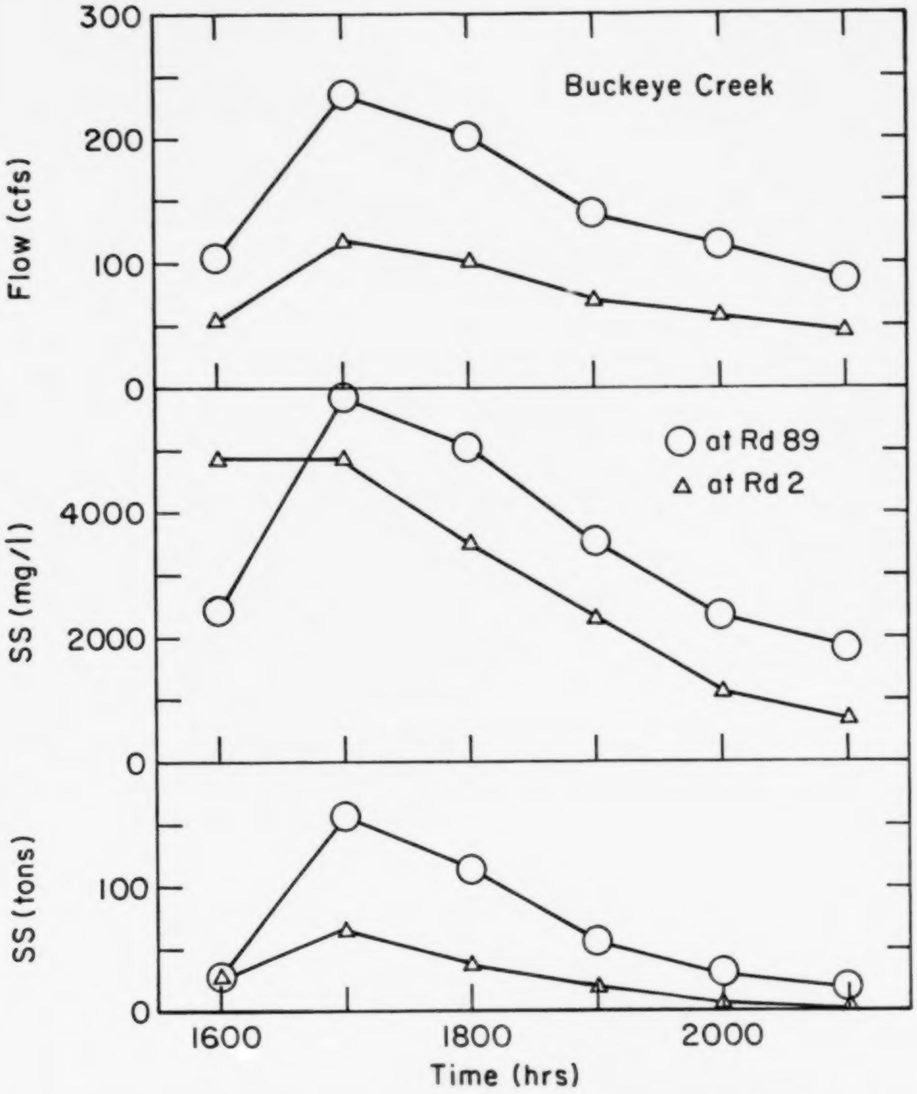


Figure 17. Flood hydrograph and sediment concentration and loading in Buckeye Creek during the February 12, 1978 storm event.

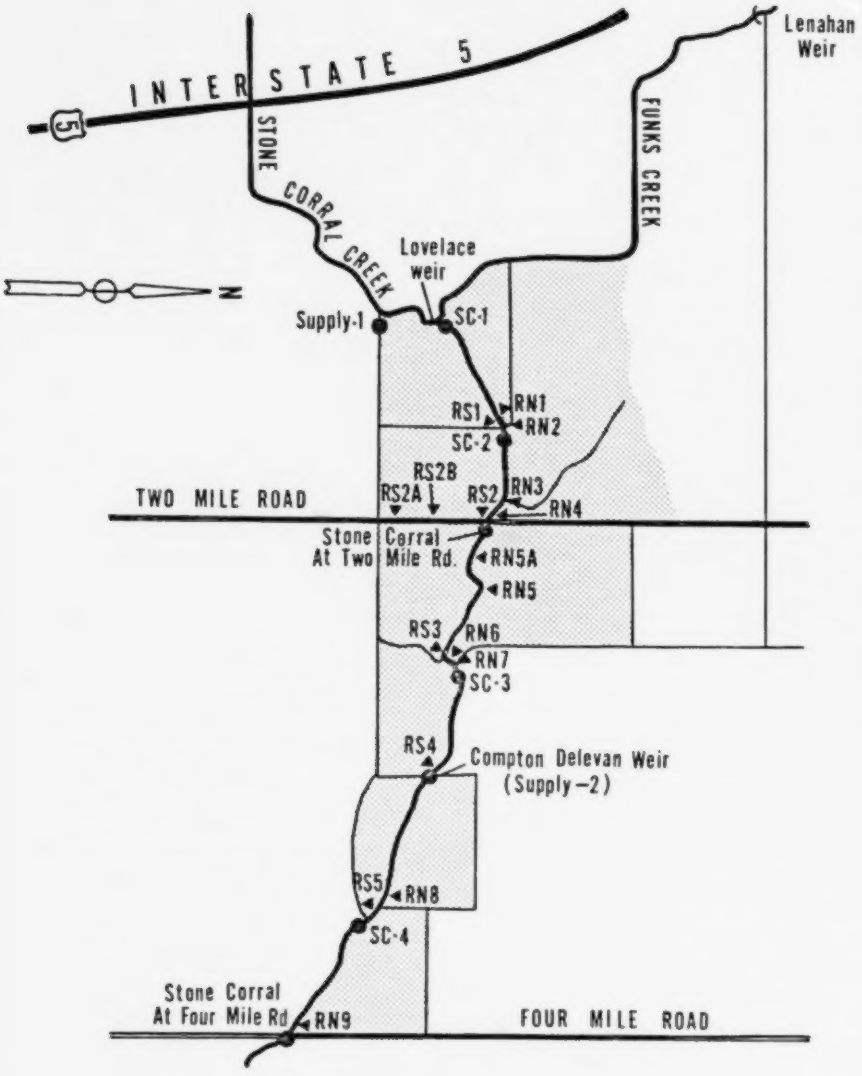

INTERSTATE 5
5
STONE CORRAL CREEK
FUNKS CREEK
Lenahan Weir
Lovelace weir
N
Supply-1
SC-1
RS1
RN1
RN2
SC-2
RS2B
RS2A
RS2
RN3
RN4
TWO MILE ROAD
Stone Corral At Two Mile Rd.
RN5A
RN5
RS3
RN6
RN7
SC-3
RS4
Compton Delevan Weir (Supply-2)
RS5
RN8
SC-4
Stone Corral At Four Mile Rd
RN9
FOUR MILE ROAD

Figure 18. Location map of three mile reach of Stone Corral Creek where the transport, deposition, and resuspension of suspended matter was investigated.

TABLE 12. SOIL LOSS AND RUNOFF VOLUME FROM THE CONTRA COSTA AND HILLGATE SOILS AT VARYING SLOPE ANGLES

Soil Series	Slope (%)	Initial Moisture (%)	Rainfall Rate (mm/hr)	Soil Loss (g/m²)		Runoff Volume (ℓ)		Mean Soil Loss Ratio†
				total	corrected	total	corrected	
Contra Costa	3	32.9	76	621	621	21.0 ab††	21.0 a	0.54
	9	32.8	76	1147	1147	21.9 a	21.9 abc	1.00
	12	33.7	76	1295	1295	22.0 a	22.0 abc	1.13
	16	33.4	76	1502	2251	21.8 a	21.8 abc	1.31
	24	32.6	76	2216	2282	22.1 a	22.8 c	1.99
	32	33.4	76	2578	2707	21.3 a	22.4 bc	2.36
	40	33.8	76	2554	2733	19.9 b	21.3 ab	2.38
Hillgate	3	17.6	76	478	478	20.3 ab	20.3	0.57
	7	17.2	76	728	728	21.7 c	21.7	0.86
	9	17.6	76	839	839	20.7 abc	20.7	1.00
	12	17.9	76	2037	2037	21.2 bc	21.2	2.43
	16	17.9	76	3013	3013	20.8 abc	20.8	3.59
	20	17.6	76	3509	3580	20.1 ab	20.5	4.27
	24	17.6	76	4733	4875	20.0 ab	20.6	5.81
	28	18.1	76	5158	5364	19.9 ab	20.7	6.39
	32	17.8	76	6115	6421	20.3 abc	21.3	7.65
	36	17.8	76	6062	6396	20.6 abc	21.8	7.62
	40	17.7	76	6806	7257	19.9 a	21.3	8.65
	50	17.9	76	7056	7832	18.9 d	20.8	9.34

† Mean soil loss ratio = mean soil loss at any slope divided by soil loss at 9% slope.

†† Means within a soil followed by the same letter are not significantly different at t = .99. Soils were not compared. Where no letters appear, there were no significant differences or differences were not compared statistically. See text for discussion.

Our study used two common soils from the Colusa Basin, the Contra Costa and Hillgate (Table 12). Contra Costa is formed from sandstone parent material of the coast range. Hillgate is formed from alluvium which originated in the coast range. Each soil was packed into 1.2 m x .6m boxes and rained on at 76 mm hr^{-1} for 30 minutes. A minimum of 4 replicates was made for each soil at slopes between 3 and 50 percent.

As in previous studies (Singer et al., 1981, Singer et al.,1982) antecedent moisture and rainfall intensity were carefully controlled during each event (Table 12). Significantly less rain reaches the soil surface at high slopes compared to low. A factor based on the percentage change in area exposed to rainfall was used to correct the observed runoff volume and soil loss for slopes equal to or over 20 percent (Table 13).

TABLE 13. SLOPE ANGLE AND CORRECTION FACTOR FOR THE SLOPE STUDY

Slope (%)	Slope (degree)	cos (slope)	Length subject to rainfall (cm)†	Length reduction (%)	Correction factor (%)
3	1.72	1	121.92	0	0
7	4.00	1	121.92	0	0
9	5.14	1	121.92	0	0
12	6.84	0.99	121.80	0.1	0
16	9.09	0.99	121.80	0.1	0
20	11.31	0.98	119.48	2.0	2
24	13.50	0.97	118.26	3.0	3
28	15.64	0.96	117.04	4.0	4
32	17.74	0.95	115.82	5.0	5
36	19.80	0.94	114.60	6.0	6
40	21.80	0.93	113.39	7.0	7
50	26.57	0.89	108.51	11.0	11

† Calculated as length of plot x cos (slope angle).

The effect of the correction factor was to increase soil loss and runoff volume at higher slopes. For Hillgate, this eliminated significant differences in runoff volume due to the reduction in rain volume intercepted. A similar effect was found for the Contra Costa soil although all significant differences in runoff volume were not eliminated.

Corrected total soil loss as a function of slope is different for each soil (Figs. 19 and 20). The relationship between soil loss ratio(s) and sine of slope angle θ is different for the two soils and different from the relationship used to predict S for the USLE (Fig. 21). The three curves are similar between 3 and 12 percent, then they diverge from each other. The

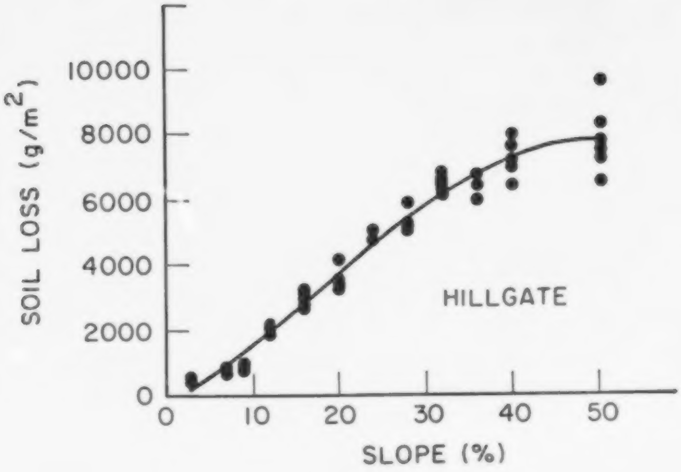


Figure 19. Soil loss as a polynomial functon of slope for the Hillgate soil.

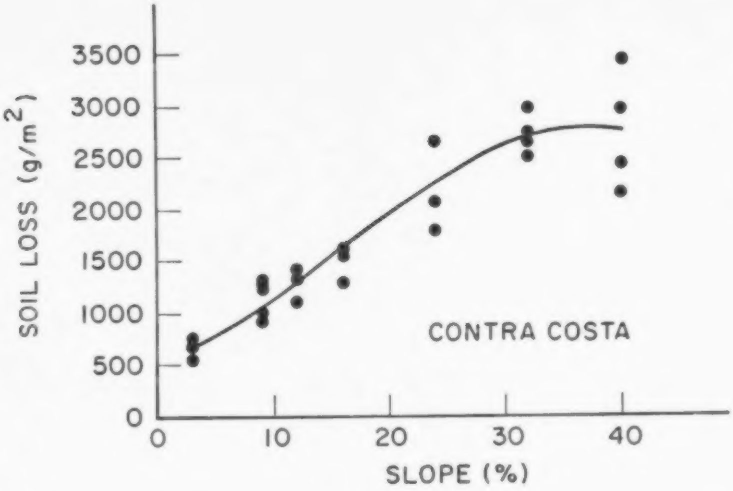


Figure 20. Soil loss as a polynomial function of slope for the Contra Costa soil.

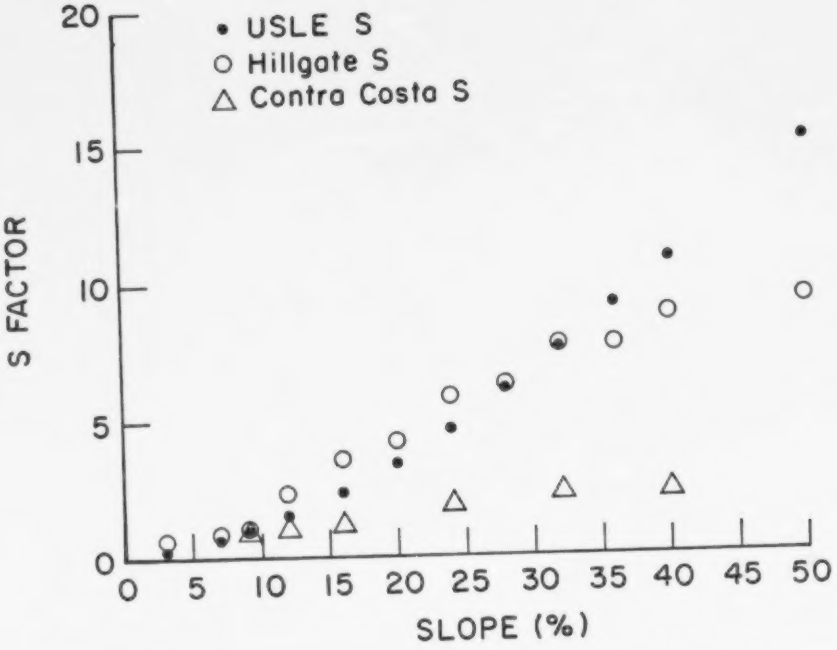


Figure 21. S factors as a function of slope calculated by the USLE equation (•) for the Hillgate (o) and the Contra Costa soils (Δ).

Hillgate and Wischmeier curves are similar up to 32 percent slope. Differences in soil erodibility should not affect the curves because the S factor is a ratio of soil loss at any slope divided by soil loss at a standard slope. The difference between the Hillgate and Contra Costa curves and equations for the curves (Eqs. 6, 7) is explained as a fundamental difference in how the soils react to erosive forces at different slopes. The Contra

$$\text{Soil Loss Ratio} = -0.12 + 10.9X + 93.13X^2 - 158.25X^3 \quad (6)$$

(Hillgate)

$$\text{Soil Loss Ratio} = 0.21 + 9.18X - 8.31X^2 \quad (7)$$

(Contra Costa)

Costa is more resistant to erosion at high slopes than Hillgate. This may be a function of its higher clay or organic matter content or to a combination of properties which increase the soils shear strength and/or aggregate stability. There does not appear to be a difference in sealing, infiltration rate, or rilling between the soils.

The USLE assumes that the S factor is independent from the K factor. This may be true at low slopes, but the results from this experiment show that at higher slopes the two factors may not be independent.

The Hillgate curve indicates that as slope increases beyond 40 percent the effect of slope on erosion begins to decrease. This may reflect a change in erosion process. That is, one may expect more gully erosion and mass wasting at slopes over 40 percent and less sheet and rill erosion. This needs to be tested at longer slope lengths. The 1.2 m slope length at which this work was done may limit the transport capacity of the runoff which, in turn, would decrease the erosion at higher slopes.

For the purpose of the sediment production analysis made for the CBD watershed, we do not have sufficient data to develop an S factor curve for each of the 17 most erodible soils. We have assumed that either the Wischmeier Eq. 5 or Hillgate Eq. 6 relationships are correct. At slopes below 32 percent the error in this assumption is small unless most of the soils of the watershed act like Contra Costa rather than Hillgate. If most soils act like Contra Costa, then Eq. 5 will overpredict the S factor by more than 2X at slopes over 20 percent.

Above 40 percent considerable uncertainty exists in the S factor regardless of which curve is selected. Because of this, we used Eq. 3 without correction for estimating potential soil loss in the watersheds.

K factor analysis--

Several studies in California (Munn and Singer, 1981; Trott, 1981; Singer et al., 1980) have shown that soil erodibility is influenced by factors which are not accounted for in the K factor nomograph (Wischmeier et al., 1971). Among the soils of the level to nearly level land in the Colusa Basin are over 182,000 acres of sodium affected soils. Considerable research effort has been expended to understand the role of soil chemical properties in soil aggregation and aggregate stability (e.g., Allison, 1956; Emerson, 1967; Aylmore and Sills, 1978) but these relationships have not been extended to soil erodibility and soil erosion.

This detailed technical study was designed to determine i) does exchangeable sodium affect soil erodiblity? ii) what level of exchangeable sodium percentage (ESP) is important in affecting soil erodibility? and iii) are there important interactions between ESP, other soil properties and soil erodibility?

Three experiments were used to answer these questions. In the first, three nearly identical samples of A horizon from the Colusa series (typic natraquolls) (Table 14) were collected in Colusa County. Each sample was air-dried, sieved to pass a 4-mm sieve, packed into 60 x 60 x 30-cm boxes at 9 percent slope, and water was applied with the small rainfall simulator previously described.

The three Colusa samples were nearly identical in silt content, but varied somewhat in sand and clay (Table 14). The largest difference was between Colusa 1 and Colusa 3. Total carbon did not vary significantly among the samples. Exchangeable Na (ESP) was different for the three samples.

TABLE 14. SELECTED PROPERTIES FROM THE COLUSA, CONTRA COSTA, HILLGATE, PESCADERO, AND SACRAMENTO SERIES A HORIZON'S USED IN THE EROSION EXPERIMENTS

Soil Series	Sand (%)	Silt (%)	Clay (%)	Exchangeable Na (%)	CEC (me/100g)	Total Carbon (%)	Relative occurrence of clay minerals[a,b]
Colusa 1	5	63	32	73	24	1.3	-
Colusa 2	11	63	26	54	26	1.4	-
Colusa 3	16	62	22	4	23	1.6	-
Pescadero	13	49	38	15	29	0.6	-
Sacramento	2	43	54	4	40	1.2	-
Contra Costa	3	61	36	.05	37	2.4	Sxxxxx,Kxx,Vx,Mx,C/VI trace
Hillgate	40	43	17	.2	15	1.9	Sxxxx,Vxx,Kxx,Mx,C/VIx

[a] S: Smectite, K: Kandite, V: Vermiculite, M: Mica, C/VI: Chlorite-Vermiculite intergrade.

[b] The occurrence is: xxxxx very abundant, xxxx abundant, xxx very notable, xx notable, x insignificant.

Erodibility of Colusa 1 and 2 did not differ significantly, but both had significantly higher erodibility than Colusa 3 (Table 15). Mean runoff volume was the same for all three samples. The high exchangeable Na content of Colusa 1 and 2 decreased their aggregate strength and increased their detachability compared to Colusa 3. Soil losses from Colusa 1 and 2 were 24 and 21 percent greater than from Colusa 3. These results were not unexpected, but it was surprising that a 19 percent increase in sodium (Na) (54 to 73 percent) did not result in a higher sediment loss from Colusa 1 compared to Colusa 2.

Kemper and Koch (1966) measured aggregate stability for 516 soils, of which eight had ESP > 5 and none had ESP > 25. For soils with ESP > 20, aggregate stability was nearly zero. In addition, they reported that the stability of a soil with 22 percent clay content would be 4 percent lower than a soil with 32 percent clay content. The difference in clay content could partially explain the different behavior observed for the three Colusa samples.

To further explore these relationships, we replaced the natural cation assemblage on the Pescadero and Sacramento samples with calcium (Ca), magnesium (Mg), or sodium (Na) (Table 16). For this experiment a small, desk top water applicator was built (Figure 22). It had a source of pressurized air, a water reservoir and adjustable water outlet. The water volume applied to the sample (1750 ml), the application rate (350 ml/min) and the distance between the nozzle tip and sample (~ 50 cm) were kept constant. Each soil sample was packed into a 15 cm diameter by 4 cm deep sample holder and eroded for 5 minutes. Prior to and following each erosion event, the water application rate was measured. The system was not designed to simulate natural

TABLE 15. EXCHANGEABLE SODIUM PERCENTAGE, MEAN RAINFALL INTENSITY, ANTECEDENT SOIL MOISTURE CONTENT, SEDIMENT WEIGHT AND LOSS RATE, AND RUNOFF VOLUME FOR THREE SAMPLES OF THE COLUSA SERIES

Sample #	Exchangeable Na (%)	N	Mean Rainfall intensity (mm/hr)	Mean Antecedent H_2O (%)	Mean Sediment Loss		Mean Runoff volume (ℓ)
					Weight (g/m^2)	Rate ($g/m^2/min$)	
Colusa 1	73	4	76.7 a[†]	38.2 a	2991 a	99.7	10.6 a
Colusa 2	54	5	77.7 a	33.2 a	2903 a	96.8	10.9 a
Colusa 3	4	5	77.7 a	29.6 a	2403 b	80.1	10.8 a

[†] Numbers followed by the same letter are not significantly different at 0.01% probability level by Scheffé's test.

N = Number of replicate erosion events.

TABLE 16. ERODIBILITY OF SACRAMENTO AND PESCADERO A HORIZONS WITH DIFFERENT EXCHANGEABLE CATION TREATMENTS

Soil Series	Natural Cation Content (me/100g)					Treatment	Sediment Loss (g)	Runoff Volume (ml)	"Rainfall" Intensity (ml/min)
	Ca	Mg	Na	K	H				
Sacramento	19.9	18.1	1.8	0.6	0.0	None	3.82 b[*]	308 ab	68.4 ab
						100% Na	11.68 a	320 ab	68.2 ab
						100% Mg	2.88 b	299 a	66.2 a
Pescadero	6.4	16.1	4.4	0.6	1.6	None	14.80 a	338 b	69.6 b
						100% Ca	4.43 b	293 a	68.0 ab
						100% Mg	4.53 b	295 a	68.0 ab

[*] Numbers followed by the same letter are not significantly different at 0.01% probability level according to Schaeffé's test.

rainfall, but it allowed us to apply fairly uniform amounts of distilled water at controlled rates to the sample surface.

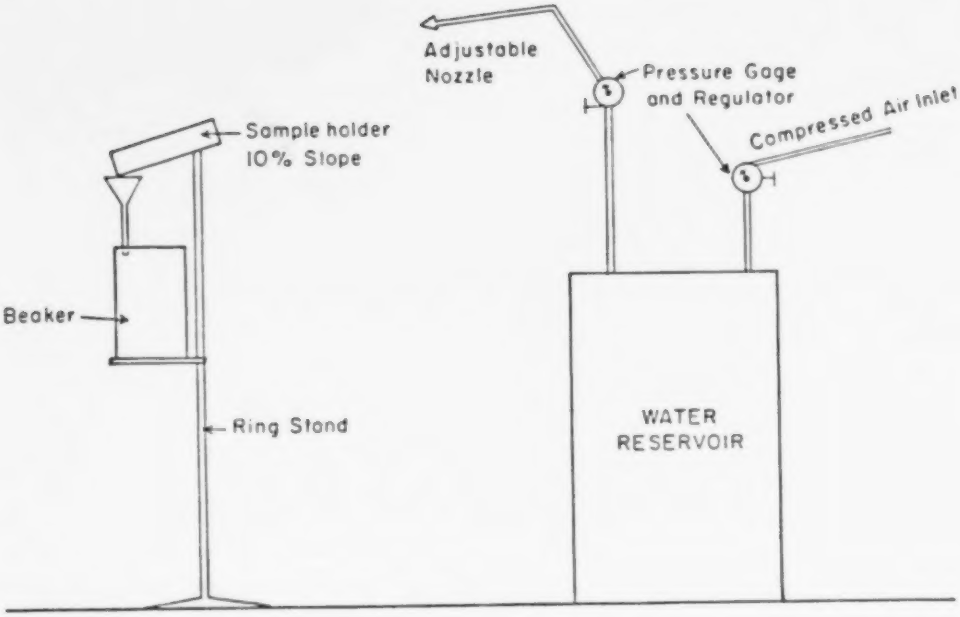


Figure 22. Water application device used in the experiments involving exchangeable sodium.

Sediment loss from the natural Pescadero samples was 3 times more than either the Ca or Mg saturated samples. When the natural (low ESP) Sacramento samples were Na saturated, erodibility increased by 3 times. There was no significant difference in erodibility between the Mg saturated and the natural Sacramento (Table 16). No significant difference was found in erodibility between the Ca or Mg saturated Pescadero samples and the natural (50 percent Ca, 45 percent Mg) or Mg saturated Sacramento samples.

Emerson and Bakker (1973) showed that a slightly higher ESP was required to cause clay dispersion when the complementary ion was Ca instead of Mg. They experimented with pure clay systems at an ESP range between 3-12. Our lowest ESP was 15 for the natural Pescadero, and we measured erosion rather than dispersion so the results are not entirely comparable. The importance of Na in increasing erodibility at moderately high ESP and at ESP = 100 is clear from this experiment.

The term "soil erodibility" is used loosely here, because the erosion system is small, "rainfall" rates were low and energy was small. Soil detachment by rain-splash may be a better term. Rill development was not observed on the small plots. Soil movement was a combination of rain-splash transport and overland flow (interrill) transport. Runoff volume decreased significantly from the natural Pescadero to the Ca or Mg saturated samples.

Runoff volume did not change significantly for the Sacramento samples. The Na decreased aggregate stability which increased susceptibility to rainfall detachment. The decreased aggregate stability resulted in decreased infiltration and increased runoff. Runoff volume was highest for the high ESP treatments of the two soils.

The final experiment was designed to determine the lowest ESP which significantly influenced erodibility. The same apparatus and techniques were used in this and the previous experiment. We used the Hillgate and Contra Costa soils for this experiment (Table 14). Contra Costa has 3 percent sand compared to Hillgate's 40 percent. The silt plus very fine sand content for Contra Costa is 62 percent and Hillgate's is 56 percent. Contra Costa has a higher total carbon and clay content, the same natural structure, and slightly lower permeability than Hillgate. The erodibility nomograph K value for this Contra Costa sample is 0.27 and for Hillgate 0.33 (Wischmeier et al., 1971). Both soils are naturally low in Na (Table 14).

Experimental conditions, particularly water application rates, were better controlled for the Contra Costa experiments than for the Hillgate experiments. Considerable difficulty was encountered in maintaining a uniform rate of water application in the Hillgate experiments. This difficulty may have caused some of the lack of statistical differences in sediment weight data for the Hillgate soil. Initial soil moisture contents were significantly higher for the 75 and 81 percent Na levels. This did not appear to affect runoff volume or sediment weight, which might have been higher had the initial water content affected the experiment. In earlier experiments we found that higher antecedent moisture contents increased erosion (Singer et al., 1978). We had some difficulty in preparing the Contra Costa samples at the higher ESP.

Erodibility of the two soils increased significantly with the addition of as little as 2 percent Na to the exchange complex (Table 17). For Contra Costa, changing from a Ca saturated exchange complex to one with 2 percent Na caused a 70 percent increase in sediment loss with no significant increase in runoff volume. Sediment loss from Hillgate for the same ESP change increased 22 percent with no significant increase in runoff volume.

Maximum soil loss for Contra Costa was measured at 12 percent Na (Fig. 23). This value is bracketed by two lower soil loss measurements at 8 and 19 percent Na. Apparently within this range Na had its major effect on aggregate stability. Above this level of Na, no additional effect was noted. Sealing of the Contra Costa soil surface at elevated ESP did not appear to be a major reason for the increased soil loss. Runoff volume did not increase with increasing ESP as it should if surface sealing occurred. The runoff results were probably influenced by the small sample size, and the low water drop impact energy. Enhanced surface sealing would be expected under higher raindrop energies.

TABLE 17. WATER APPLICATION RATES, INITIAL MOISTURE CONTENTS, RUNOFF VOLUME, SEDIMENT WEIGHT, AND SEDIMENT CONCENTRATION FROM HILLGATE AND CONTRA COSTA SOILS WITH VARYING ESP

ESP (%)	Mean Water Application Rate (ml/5 min.)	Initial Moisture (%)	Runoff Volume (ml)	Sediment Weight (g)	Sediment Concentration (mg/ml)
Hillgate					
0	353	18.8 a	324 a	11.5 a	35.8 a
2	346	18.7 a	325 a	14.1 bcd	43.3 bc
4	359	18.4 a	332 ab	15.6 cd	47.1 c
12	359	19.5 a	334 ab	15.4 cd	46.1 c
16	353	18.7 a	346 bc	16.3 d	47.2 c
42	325	18.8 a	344 bc	14.9 bcd	43.5 bc
69	336	19.2 a	354 c	13.0 ab	37.0 ab
80	338	19.2 a	359 c	13.9 bc	39.0 ab
Contra Costa					
0	345	34.3 a	327 cd	3.7 a	11.5 a
2	353	33.3 a	340 d	6.3 b	18.2 b
4	349	33.9 a	341 d	8.1 c	24.0 c
8	347	33.9 a	330 d	11.3 d	34.2 d
12	350	35.0 a	335 d	13.9 e	41.2 f
19	344	35.2 a	311 bc	11.5 d	37.0 de
42	342	34.4 a	294 ab	11.2 d	38.2 ef
75	348	38.6 b	318 c	12.8 de	40.0 ef
81	343	37.7 b	284 c	11.7 d	41.2 f

Values followed by the same letter within soils are not significantly different at the 5% level by Scheffé's Test. Soils were not compared statistically.

Maximum soil loss for Hillgate was at ESP = 16. There was no statistical difference in soil loss between ESP = 2 and 42. We found a small decrease in erodibility at ESP > 42. This behavior might be due to rapid surface sealing which increased resistance to soil detachment. Runoff volume increased significantly as ESP increased, probably because the surface seal formed and reduced the infiltration rate.

The major difference between these two soils besides ESP is clay content. Hillgate is low in clay and is more erodible than the Contra Costa. Emerson (1964, 1967) showed that Ca saturated kaolinite disperses more than Ca-illite or montmorillonite in water. In another study, simulated rainfall caused remolded aggregates of kaolinite to slake rapidly while montmorillonite and illite did not (Rose, 1962). Because of the similarity in clay

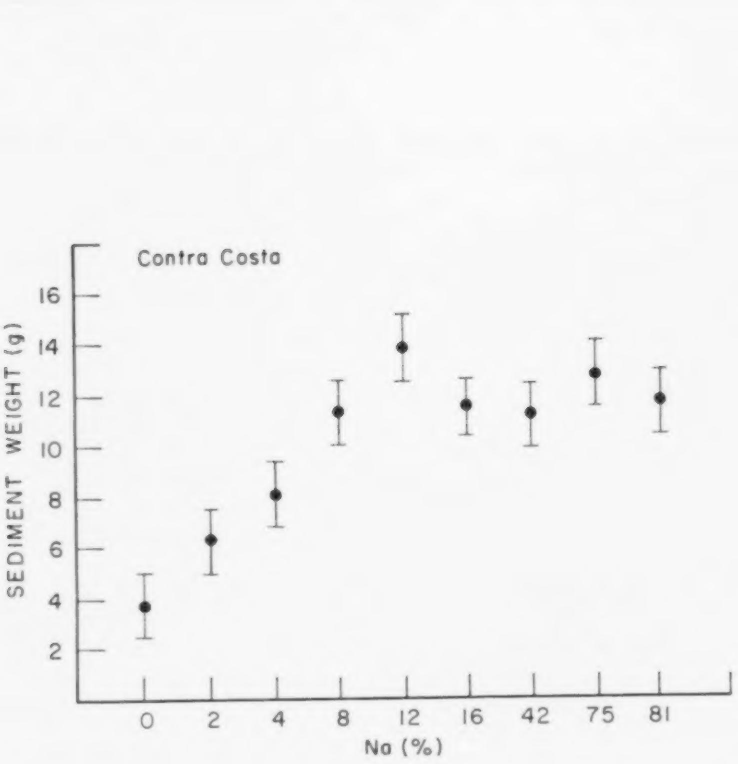


Figure 23. Soil loss as a function of ESP for the Contra Costa soil.

mineralogy of the soils, differences in their behavior cannot be ascribed to clay mineralogy.

Cation exchange capacity (CEC), which is partly a reflection of amount and type of clay, affected the response of the soils to Na, although the effects of clay cannot be separated from those of CEC in this experiment. Reeve et al. (1954) showed that the response of modulus of rupture, and air and water permeability to ESP was strongest at a high CEC for eight western states' soils. Our data show a similar effect of CEC.

These data support the hypothesis that soil erodibility is higher than the nomograph K value predicts on some soils in the Colusa Basin drain watershed. Erodibility is not equivalent to soil loss, but higher erodibility increases the likelihood of soil erosion. As yet, the source of the sediment in the drain has not been identified. It is clear that Na affects erodibility, and that this is one potential source for the high sediment load of the drain.

The small water applicator and rainfall simulator are useful tools for testing hypotheses, but it would be useful to experiment on larger samples and a wide array of soils. Until such time as this is done, it would be a prudent management technique to assume a higher K value for soils with

ESP > 2. The data for the Colusa soil indicate that a 20 percent increase in K value may be appropriate for these soils. Further work is needed to quantify the critical ESP and to elucidate the clay, CEC, ESP, erodibility interaction.

Discussions--

Although the USLE is not designed for watershed studies, it provides qualitative and quantitative estimates of relative soil erosion from various portions of the watershed. Numerous sources of error exist in the analysis. Of these, estimates of the cover factor may vary by several orders of magnitude and, as we have shown, the S value may be overestimated at high slopes by over 2X. The K value, may be underestimated by as much as 20 percent for soils with ESP $\geq$ 2. Yearly variation in the amount, intensity, and timing of precipitation will greatly affect the sediment production in the basin.

Providing one keeps these quantitative uncertainties in mind, it is possible to qualitatively separate the watershed into areas of similar potential sediment production and to discuss best management practices (BMPs) for these areas. It is clear from the preceding discussion that the land with slopes in excess of 30 percent should be separated from that with slopes less than 30 percent. We have chosen to divide the watershed into areas with slopes less than 15 percent, 15 to 30 percent, and in excess of 30 percent. Within the two lower slope groups, we discuss best management practices for cultivated irrigated lands and cultivated non-irrigated lands.

Detailed BMP's have been developed and cost evaluations for them have been made for other watersheds in California (USDA, 1979b) and for two watersheds in the CBD (USDA 1979c,d,e). We do not provide detailed engineering design criteria because such criteria must be site specific, and because literature exists for agriculture (e.g., Stewart et al., 1975; Foster, 1973; Ayres, 1972), urban (Becker and Mills, 1972) and second home (White and Franks, 1978) areas.

Bailey and Waddell (1979) identified seven criteria for identifying BMPs. These are i) agronomic effectiveness, ii) environmental effectiveness, iii) economic efficiency, iv) equity, v) social acceptability, vi) implementability, and vii) energy requirements.

Any practice designed to stop erosion and/or sediment delivery must be effective without being an impediment to continued agricultural productivity. If a practice meets these tests, it has to be economical and the costs have to be shared equitably between the landowner and the water users whose water is being protected. These are considered in the following discussion of BMPs.

BMPs may be subdivided into those which stop or reduce soil erosion on site, and those which prevent sediment from reaching a body of water. The first subdivision is best in the long term because two goals are achieved. First, soil and soil productivity is preserved and second, water quality is protected. It is BMPs which reduce erosion which are considered here. The second subdivision of practices is necessary in the short run to stop sediment from reaching the CBD from existing severe problem areas. Long range solutions should rely on practices which reduce erosion at its source. Standard practices such as water diversion or sediment retention ponds can be used where appropriate. Gullies which have been considered as point sources of sediment need to be treated in both ways. First, sediment produced by gullies must be stopped before they enter waterways. Second, the gullies must be reclaimed and removed as sources of sediment.

On the west side of the Colusa Basin, on soils with slopes greater than 30 percent, the dominant uses are range and forestry with range being the most important economically and most extensive. Unlike cropland, there is no long history of tested erosion control practices for rangeland. Studies have shown that poor management can cause deterioration of rangelands and decreased range productivity (e.g., Busby and Gifford, 1981; Holechek, 1980; Evans, 1977; USDA, 1976; Kraebel and Pillsbury, 1934).

Livestock management can be the most effective and least costly method of erosion control. A wide range of practices are available to the rancher who wants to control soil erosion and maintain productivity of the range. These are grouped by the SCS into three broad management types: vegetation management, facilitating, and accelerating practices (USDA, 1976). Vegetation management includes proper grazing use, deferred grazing depending on plant growth, and planned grazing. Facilitating is used to control or influence animal movements. This is accomplished by developing water and trails, establishing walkways in wet areas, fencing, and proper location of salt licks. Accelerating practices are those that cause plant growth to be faster than under unmanaged conditions. Seeding, brush management, fertilizing, water spreading and controlled burning are examples of accelerating practices. Any and all of these are suitable for areas in the Basin.

The Balcom, Dibble, and Millsholm series which may account for over 21 percent of the soil erosion in the watershed (Table 3) will respond to fertilization, and on slopes less than 50 percent can be seeded with improved species to increase production (Andrews, 1972). The deeper mapping units are particularly suitable for improvement because of their water holding capacity. Several of the soils from Table 3 (Altamont, Ayar, Contra Costa, Nacimiento, Sehorn, and Shedd) are considered highly productive particularly in foothill positions where they can be managed. On steeper sites, these soils are usually more shallow and are more difficult to manage (Begg, 1968). Most of these soils will respond to nitrogen, phosphorus, and sulfur fertilization.

A management program which includes acceleration of plant growth and animal management can have multiple positive benefits. First, the rancher who invests money in range improvement will gain extra income from the increased production in the short term. This may be off-set by reduced short term production on areas where animal numbers or grazing period must be reduced. In the long term, productivity on the entire range should improve. Downstream, decreased suspended sediment due to reduced erosion will benefit water users. Similar range management strategies can be used on slopes less than 30 percent. In order for management practices such as walkways, stock trails, forage quality improvements, and fencing to be economical, the costs associated with the practices will have to produce yield benefits to the rancher who implements the practices, or the cost of practices will have to be subsidized. Management practices which result in animal yield increases have the advantage over sediment retention structures that they do produce income which offsets some of the costs involved in their implementation. The most productive best management practice will be a package of practices designed to fit the particular area.

Roads have been identified as a major source of sediment. Closure of dirt roads in wet weather, permanent closure of roads to all but emergency (fire) use, and proper installation of water bars, culverts, and water spreaders can greatly reduce sediment from roads. The appropriate practice or set of practices must be determined for each road segment to be treated.

The area of low foothills which has slopes between 15 and 30 percent is grazed, often in rotation with dry farmed grain. Irrigation is, for the most part, used on the level or nearly level lands of the basin. On these less steeply sloping areas, the more traditional practices such as contour cropping, and no till or minimum tillage agriculture are suitable means of reducing soil loss. The thrust of this recommendation is to decrease the percentage of area which is bare or with a low cover percentage during the winter months and to increase the efficiency of water use. If water runoff can be reduced by improving the infiltration rates of these soils, crop growth should improve due to the higher soil moisture status (particularly in years of marginal rainfall), and soil loss in runoff should be reduced. Infiltration rates can be maintained or improved by reducing compaction due to excessive traffic and operation of equipment when the soil is too wet. Chemical amendments or incorporation of organic matter can also improve water entry into the soil.

An effort needs to be made to educate landowners, farmers, and ranchers to the long and short term benefits which can be gained from better land management. The short-term benefits from better management are higher profits, while the long-term benefits are erosion control, long-term productivity improvement, and reduced sediment in the Colusa Basin Drain.

Action agencies such as the USDA Soil Conservation Service, State Department of Water Resources, Water Quality Control Boards, University of California Cooperative Extension in cooperation with local government bodies, and private organizations should be the implementors of the education program. Once the benefits are understood, actual implementation of practices can be facilitated by these organizations.

Sediment Production from Irrigated Fields

Sediment production from irrigated fields was monitored in rice, tomato, and corn fields in the study area.

Flooded rice culture--

Sediment production from paddy rice fields was studied by monitoring the inflow and outflow of suspended solids (SS) from the rice fields (Henderson et al., 1974; Tanji et al., 1976, 1977). It was shown that the inflow of water to the rice fields varied from 6.3 to 12.2 ac-ft/ac while the surface runoff varied from 0.6 to 4.5 ac-ft/ac. The average surface inflow was 8.7 ac-ft/ac and the average outflow from the rice fields was 2.6 ac-ft/ac. On the average about 30 percent of inflow water was discharged from the rice fields.

The concentration of SS in the supply water varied from 10 to 150 mg/ℓ. The concentration of SS in the outflow was uniformly lower than that of inflow. The mass of SS discharged varied from 40 to 330 lbs/ac or 10 to 35 percent of that brought in with the supply water. These data indicate that flooded rice fields act as settling basins for SS.

Furrow-Irrigated Tomato Field--

Intensive irrigation tests were conducted twice in a tomato field. These tests involved measuring inflows and outflows of water and SS in furrows from half-hour to two-hour intervals over the duration of the irrigation. The detailed data of a 30-acre portion of the 173-acre tomato field was monitored on June 20 and 21, 1978 (Tanji et al., 1978). The test section had 210 furrows with furrow lengths of about 1,245 ft and a slope of 0.001. The source of supply water was a 1,800 gpm deep well. The inflow to the furrows ranged from 3 to 15 gpm, as measured by the bucket and stop watch method. V-notch weirs were installed at the end of furrows to measure outflow from the individual furrows. A 2-ft rectangular weir was installed in the return flow ditch and total outflow from the furrows was measured every half hour. The total amount of water applied to this 30-acre tract was 7.63 ac-ft or 3.0 surface inches while the tailwater produced from the field was 2.40 ac-ft or 0.9 inches, i.e., 30 percent of the applied irrigation was lost as tailwater. Irrigation water was applied to the field for a total of 27 hrs and tailwater production occurred over 18.5 hours.

Frequent samples were obtained of the outflow and inflow waters to determine SS, turbidity, and electrical conductivity (EC). Table 18 gives a summary of the results. The concentrations of SS in the supply water ranged from 1 to 2 mg/ℓ whereas the concentration of SS in the tailwater discharged ranged from 640 to 1,140 mg/ℓ, for an average of 887 mg/ℓ. These large increases in sediment concentration in the tailwater are attributed to sheet erosion from the furrows and channel erosion from return flow ditch. The sediment load produced from this one irrigation over a 30-acre site was 1.6 tons as measured at the weir in the return flow ditch, and 2.9 tons as measured at the drain canal. The unit mass emission of SS during this irrigation was 105 lbs/ac at the weir and 193 lbs/ac at the drain canal as compared to the 1.04 lbs/ac brought in with the applied well water. The results of this test are similar to a 1975 test run conducted in a furrow-irrigated tomato field in the Panoche Water District (Tanji et al., 1976) where tailwater production was 24 to 29 percent of the inflow.

TABLE 18. SUMMARY OF 1978 SEDIMENT PRODUCTION TESTS IN FURROW-IRRIGATED TOMATO AND CORN FIELDS NEAR DUNNIGAN

Description	Tomato field		Corn field
	6/20-21/78	7/22-23/78	6/23/78
Area, ac	30	23	10.5
Furrow length, ft	1,245	1,245	2,600
Furrow slope	0.001	0.001	0.0025
Inflow rate into furrows, gpm	7.3	11.0	34.5
Total irrigation, ac-ft	7.63	7.06	6.18
Total irrigation, inches	3.0	3.7	7.06
Total runoff, ac-ft	2.40	2.97	0.79
Total runoff, inches	0.9	1.55	0.90
Total runoff, %	30	42	13
SS in supply water, mg/ℓ	1.5	5.0	94
SS in supply water, tons	0.016	0.048	0.79
SS in supply water, lbs/ac	1.04	4.2	150
SS in runoff, mg/ℓ	481/887	171	1,950
SS in runoff, tons	1.57/2.90	0.692	2.10
SS in runoff, lbs/ac	105/193	60	399

A second test was conducted on July 22 and 23, 1978, in the eastern 23-acre portion of this tomato field nearest the main drain and flow structure. The total number of furrows involved were 162 with furrow lengths of 1,245 ft. The inflow during 23.5 hours of irrigation was 7.06 ac-ft or 3.7 surface inches while the tailwater outflow was 2.97 ac-ft or 1.55 inches. This 2.97 ac-ft of runoff was 42 percent of the applied water. The SS concentration in the irrigation water was 5 mg/ℓ and in the tailwater from 30 to 1,410 mg/ℓ or an average of 170 mg/ℓ. The sediment load introduced by the supply water was 0.048 tons while the tailwater contained 0.692 tons. On a unit surface area, 4.2 lbs/ac of SS were introduced into the furrows and 60 lbs/ac were discharged.

A comparison between these sediment production tests showed that the sediment discharged from the first irrigation test was about three fold greater than the second test mainly because this tomato field was cultivated periodically up to the first test but not prior to the second test. the sediment production was smaller in the second test because the soil surface was undisturbed. The other significant finding was the substantial pickup of sediments between outflow from furrows and discharge into the drain from increased current velocity and channel erosion.

Furrow-irrigated corn field--

A similar tailwater-sediment test run was made on a 10.5 acre portion of a 146-acre furrow-irrigated corn field on June 23, 1978. In this test 70 furrows with a length of about 2,600 ft and a slope of 0.0025 were irrigated by 2-inch siphons from a head ditch (Tanji et al., 1978). The flow into the furrows was measured by taking the difference in head between the water surface elevation in the supply ditch and the furrow, and using a chart of head vs flow for various inside diameter siphons. The amount of irrigation water applied was 6.18 ac-ft or 7.06 surface inches. The tailwater outflow was 0.79 ac-ft or 0.90 surface inches, which is 13 percent of the applied water.

The concentrations of SS in the supply water ranged from 41 to 278 mg/ℓ with an average of 94 mg/ℓ, while that in the tailwater ranged from 1,800 to 4,820 mg/ℓ with an average of 2,930 mg/ℓ. The concentration of SS at the drain canal ranged from 372 to 2,570 mg/ℓ with an average of 1,950 mg/ℓ. The sediment concentration was lower at the drain canal than at the end of the furrows since some of the sediments were deposited in the return flow ditch due to reduced current velocities. In terms of mass of SS, the SS load into the furrows was 0.79 tons or 150 lbs/ac and the sediment discharge for the outflow was 2.10 tons or 399 lbs/ac for a net pickup of 249 lbs/ac. The higher inflow and the steeper slope for the corn field as compared to the tomato field contributed to greater sediment production.

Sediment Characterization in Channels

Field and laboratory experiments were conducted to characterize the suspended load and the bed materials. These sediment characterizations included particle sizes, bed shear stress, and the sediment components. Such characterization aids in understanding sediment production, transport, and deposition.

Particle size analysis--

Samples of bed material obtained with a ponar dredge from beneath the water column along various reaches of the CBD, as well as its tributaries after the recession of storm runoffs, were subjected to particle size analysis by dry sieve, wet sieve and hydrometer methods. For more information about these methods the reader is referred to Mirbagheri (1981).

The size distributions of bed materials found in the samples are plotted as cumulative curves showing the frequency distribution of grain sizes. The results indicate that the sediment in the study area is divided into eight size categories; one in the gravel range, three in the sand range, three in the silt range, and one in the clay range. For most samples, sand-size materials were predominant. The cumulative size frequency curves indicate that the grain size distribution varied from 5.6 to 0.75 mm for gravel and sand, and from 0.05 to 0.0008 mm for silt and clay fractions. In general, there was uniform distribution of grain sizes with sand sizes comprising about 60 percent of the total.

The size fraction data for sediments deposited in Buckeye Creek was sampled after the winter flood runoff period. Figure 24 contains size fraction data on bed sediment taken from 0.5 mile upstream in Buckeye Creek from CBD. The grain sizes varied from 4.75 to 0.075 mm (curve C and D). These

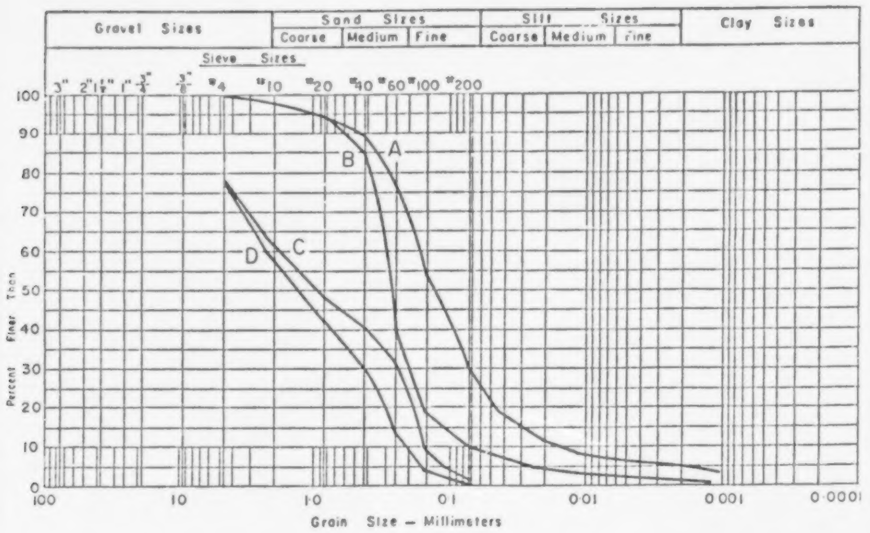


Figure 24. Particle sizes of deposited materials in the surface of Buckeye Creek at Road 2 (curve A) and at 50 ft upstream of CBD (curve B) and beneath the surface (curves C and D) 0.5 mile upstream of CBD on May 18, 1978.

materials were mainly coarse sand and gravel deposited during the peak flows when SS concentrations were in the 10,000 to 16,000 mg/ℓ range and the current velocity was about 4.6 fps. It is believed that under such high current velocities most of the fine material that was deposited from previous storms was eroded away.

Figure 25 contains curves presenting the grain-size distribution of bed materials obtained from CBD-1, CBD-1a, CBD-1b, CBD-2 and CBD-3 in mid summer. Curves A, B, and C show the grain sizes ranged from 58 to 0.0007 mm, all in the silt and clay fractions. The curves from CBD-1a, CBD-1b, and CBD-2 stations are located in the lower reaches of CBD where the slope of the channel is small, about 0.20 ft per mile. Fine particles were deposited in this section of CBD because the current velocity drops to the lowest as compared to other stations along the CBD. Each line in these figures showing the particle size analysis represent the average of at least 30 determinations.

In general, bed material changes in response to such factors as bed roughness, channel slope, current velocities, and shear force of water. The chemical constituent of water and the chemical composition of bed material could either increase or decrease the rate and quantity of deposition. The particle size analysis data for the Colusa Basin Drainage Area indicate a wide range of size fractions in the bed samples between locations as well as

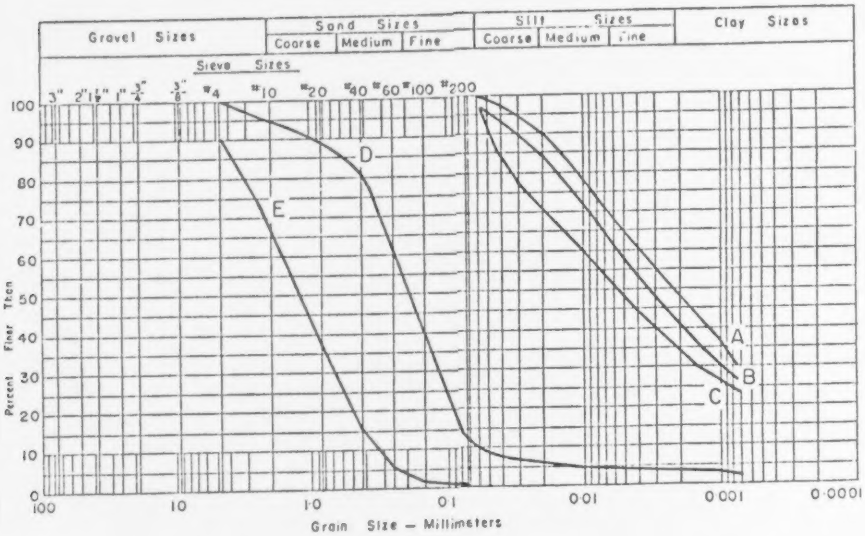


Figure 25. Particle sizes of bedload materials sampled with a dredge at CBD-1a (curve A), CBD-1b (curve B), CBD-2 (curve C), CBD-3 (curve D), and CBD-1 (curve E) on August 2, 1978.

seasons. The sand and gravel in suspension are deposited in creeks such as Buckeye and Stone Corral where current velocities were high, while some silt and clay were further transported to the main drain. At some sections of the drain (CBD-1a and CBD-1b), where the current velocities were low, silt and clay were deposited and some were transported to the outfall and discharged into the Sacramento River. The general pattern of channel bed is coarse materials for reaches with higher current velocities and steeper slopes, and fine materials for reaches of lower current velocities and milder slopes.

Determination of shear stress--

Shear stress is the most important criteria in the scouring by flow and is highly dependent upon the flow pattern. The CBD flow pattern was characterized by determining the Reynold's number. The Reynold's number ranged from 0.12×10^5 to 47×10^5 for CBD-1, and 1.9×10^5 to 36×10^5 for CBD-3 during the study period. Such high Reynold's number indicates flow was turbulent at all times in the CBD. The current velocities which control the shear stress fluctuated with time.

In addition to flow velocities, the hydraulic radius was determined by considering the trapezoidal crosssection for all stations along the CBD. The hydraulic radius of the channel at CBD-1 (outflow station) fluctuates with time and follows the same pattern as current velocities (Mirbagheri, 1981).

Since the flow is characterized as turbulent, the bed shear stress was determined by calculating the effective current velocity, $u_\star$. This term, $u_\star$, is called friction velocity or shear velocity and represents a measure of the intensity of turbulent fluctuations. The following equations were used for the determination of the bed shear stress:

$$u = u_\star \, 5.75 \log \left(3.32 \frac{Ru_\star}{\nu}\right) \tag{8}$$

$$\tau_o = \rho u_\star^2 \tag{9}$$

where u is the average current velocity (fps), $u_\star$ is the effective current velocity (fps), R is the hydraulic radius (ft), ρ is the fluid density, and τ_o is the bed shear stress.

In addition to bed shear stress, the critical shear stress of the cohesive bed material was determined using their bed samples with uniform depth. The critical shear stress is defined as the maximum shear stress at which the erosion rate is zero. The determination of critical shear stress involved the use of rotating cylinder sample preparation, and pertinent calculations. Detailed information for these procedures are presented in the annual report to EPA (Tanji et al., 1980; Mirbagheri, 1981). Critical shear stress, τ_c, is a true index of erodability and its value depends primarily on the type of bed material present. The value of τ_c would be low for noncohesive materials and high for cohesive sediment. Critical shear stress is higher in the latter because the electrochemical bond existing between the particles have to be broken before detachment and transport can occur.

The results of friction velocities, $u_\star$, the bed shear stress, τ_o, and the critical shear stress, τ_c, are plotted in Figure 26. The friction velocity profiles have the same pattern as the bed shear stress along the CBD stations. The bed shear stresses decreased with decreasing current velocities from CBD-3 to CBD-1 with the lowest values at CBD-1a where current velocities were at a minimum. Figure 26 shows the bed shear stress exceeding the critical shear stress during the peak flows for storms and the erosion of the bed material which discharged into the Sacramento River. With the exception of the winter storm, the bed shear stress was less than the critical shear stress with net deposition along the CBD stations. The net deposition was maximum between CBD-1b and CBD-1a where bed shear stress was minimum. The 1980 channel survey showed that the channel bed rose about 0.25 ft at CBD-3 and 0.75 ft at CBD-1a due to net deposition.

Suspended sediment components--

Suspended sediments in water samples taken from the CBD and the stations along its tributaries were analyzed for total suspended sediment (TSS), suspended organic matter (nonliving biomass), and suspended algae components. The results of suspended sediment analyses for summer samplings (Mirbagheri, 1981) indicate that the suspended sediment (SS) in the study area were comprised of suspended mineral sediment (SMS), suspended organic matter (SOM), and suspended algae.

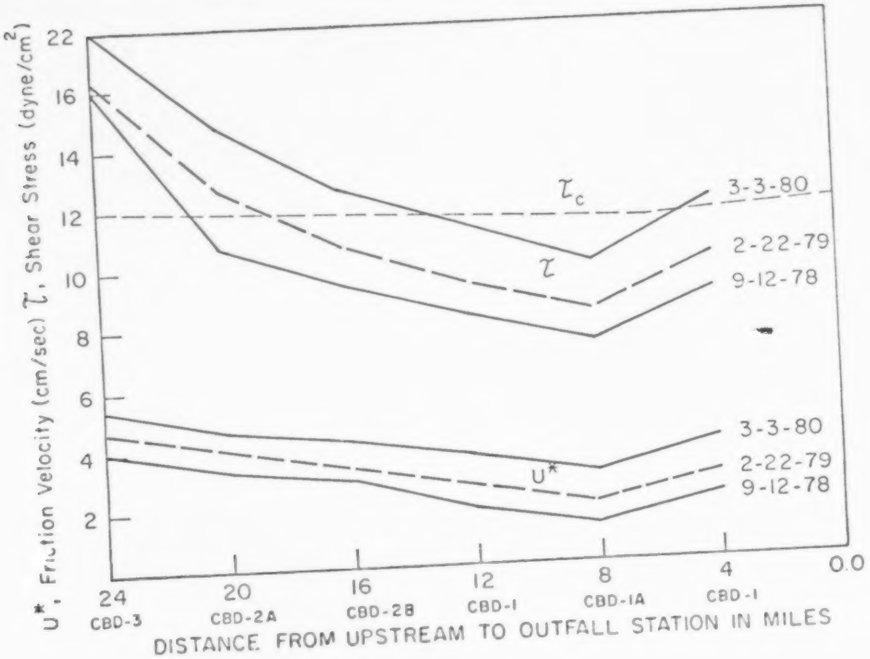


Figure 26. Hydraulic profile at CBD-1.

SMS were mainly silt and clay with a small fraction of fine sand. SMS was determined through direct measurements (gravimetric method) of TSS and measurement of SOM (loss by ignition test). Theoretically, the difference between TSS and SOM gives an estimate of SMS (TSS - SOM = SMS). Weekly analysis of water samples for SS and SOM indicate that the SMS ranged from 30 to 90 percent during the winter runoffs and from 10 to 18 percent during the irrigation season. The average SMS was 70 percent for the nonirrigation season, 50 percent for the irrigation season, and 60 percent for the annual average.

The living and nonliving organic substances contributes to the SS in the water samples. Suspended algae is an example of living organic substances. Chlorophyll-a which is an algal biomass indicator was measured and multiplied by a factor of 67 to obtain an estimate of the algae concentration. The algal biomass concentration was smallest in CBD and greatest in Glenn-Colusa Irrigation Districts' main canal and in Stone Corral Creek at Two Mile Road. The reason that water samples from Stone Corral Creek showed maximum algal concentration is due to water discharged from the rice fields. Rice fields serve as the settling basin for mineral sediment and production basin for algal biomass. The calculated percent contribution of algae to suspended sediment ranged from 3 to 43 percent with an average of 10 percent of TSS.

A third portion of the SS is SOM. SOM is introduced to CBD from erosion of soil organic matter (humus), decomposition of aquatic plants, leaves from vegetation, and discharge of municipal waste water. SOM found in CBD water consisted of biodegradable (BOD_5) and refractory organic matter. The ratio of BOD_5 to SOM ranged from 0.2 to 0.83, an average of 0.60. The SOM ranged from 16 to 80 percent, and an average of 30 percent of TSS was SOM.

Mineralogical Characterization

Mineralogical investigations pursuant to objectives of this project focused on identification of clay-size (<2 μm) phyllosilicate minerals in suspended and bedload materials from CBD and its tributaries and in the major soils within Colusa Basin. Physicochemical investigations dealt with soluble-exchangeable ion relationships.

Physical Character of Suspended Mineral Matter--

Percentages of clay-size particles in suspended mineral matter were determined for suspensions from CBD and three of its feeder tributaries during the 1979 winter rainy season, and from CBD prior to and after drainage of rice lands in August 1979. Clay-size particles constituted over one-half of the total suspended mineral solids at all sampling locations in January, and at CBD-1 within the drain in March of 1979 (Table 19). The percentage of mineral matter as clay within the drain and within the lower feeder stream, Buckeye Creek, was higher than within the central feeder stream, Stone Corral Creek, during these runoff periods. Clay constituted over 50 percent of the mineral matter suspended in CBD before and after drainage of rice lands in August 1979 (Table 20).

The data in Table 20 suggest that forces responsible for the maintenance of mineral matter in suspension during the normal irrigation season are manifested to the greatest degree within the central reaches of CBD. Concentrations of mineral matter in suspension in August 1979 were highest at CBD-2, CBD-3 and CBD-5. The percentages of suspended mineral matter as clay (< 2 μm) were lower at these locations, indicating relatively higher proportions of suspended coarser mineral particles, than at CBD-1 and CBD-6. Decrease in total suspended mineral matter from a high of 41.7 mgm/ℓ at CBD-3 to 32.1 mgm/ℓ at CBD-1, with increase in proportion of clay (63.3 percent to 73.3 percent mineral matter as clay) and of ratio of fine clay (< 0.2 μm) to coarse clay (2-0.2 μm) from CBD-3 to CBD-1, suggest net sedimentation of materials toward the lower reaches of the drain during August 1979. The concentration of suspended mineral matter at CBD-6 (9.1 mgm/ℓ) indicated low contribution to the overall suspended solids load from the northernmost reach of the drain, during the summer season.

Drainage of water from rice lands to CBD in August 1979 had perceptible effects on total suspended mineral matter and proportions of suspended clay at locations within the drain. Mineral matter in suspension at CBD-1 increased from 32.1 mgm/ℓ to 56.0 mgm/ℓ between August 9 and August 23, 1979. Significant increase in suspended mineral matter between these two dates was

TABLE 19. CLAY-SIZE MINERAL MATTER AS PERCENTAGE OF TOTAL MINERAL SOLIDS IN SUSPENSIONS – WINTER, 1979

Sampling location	Date	% clay (< 2 µm)
CBD-1	January 16, 1979	64
CBD-5	January 16, 1979	67
Stone Corral Creek		
McDermott Road	January 15, 1979	54
4 Mile Road	January 15, 1979	53
Buckeye Creek		
Road 2	January 15, 1979	65
CBD-1	March 28, 1979	63
Stone Corral Creek		
Sites Road	March 27, 1979	39

TABLE 20. CLAY CONCENTRATIONS AND PERCENTAGES IN COLUSA BASIN DRAIN SUSPENSIONS – FALL, 1979

Sampling location	Date	Clay concentration (mgm/ℓ)	Mineral matter as clay (%)	Course and fine clay as percentage of total clay 2-0.2 µm (%)	< 0.2 µm (%)
CBD-1	August 9, 1979	23.5	73.3	49.5	50.5
CBD-2	August 9, 1979	21.1	60.3	48.0	52.0
CBD-3	August 9, 1979	26.4	63.3	58.4	41.6
CBD-5	August 8, 1979	19.7	55.9	43.6	56.4
CBD-6	August 9, 1979	6.0	65.9	47.4	52.6
CBD-1	August 23, 1979	31.2	55.7	47.0	53.0
CBD-2	August 23, 1979	22.2	50.3	46.7	53.3
CBD-3	August 23, 1979	18.8	54.1	45.8	54.2
CBD-5	August 23, 1979	14.6	51.6	39.5	60.5
CBD-6	August 23, 1979	5.9	60.7	26.7	73.3

registered at CBD-2 (35.0 mgm/ℓ to 44.1 mgm/ℓ). Total suspended mineral matter at CBD-3 and CBD-5, on the other hand, was perceptibly lower on August 23 than on the earlier date in August. At all sampling locations, the percentage of mineral matter as clay (< 2 µm) was lower on August 23 than during the normal irrigation season early in August. Total clay in suspension within the drain progressively increased in concentration from the upper to the lower sampling locations as did the total mineral matter. The mineral matter in suspension at CBD-6 was low compared to other locations sampled.

Phyllosilicate Species in Suspended and Bedload Materials--

Phyllosilicate clay mineral species present in suspended and bedload sediments from CBD and from its feeder tributaries were monitored by means of x-ray diffraction analysis over 1979-1980. Samples of suspended materials were collected from the drain during the regular irrigation season, after fall drainage of the rice lands, and during the winter rainy season. Suspended material was collected from feeder streams during the winter season, and bedload samples from both the drain and feeder streams were collected during the 1979 spring season.

X-ray diffraction analyses revealed a general similarity, with respect to kinds and relative proportions, of phyllosilicate species in both suspended and bedload materials from CBD, irrespective of time and location of sampling. Chlorite and kaolin were present in highest proportions in coarse clay (2-0.2 µm) fractions of suspended material within the drain (Tanji et al., 1980b). Moderate amounts of mica and smectite and trace to moderate amounts of vermiculite-chlorite intergrade were present in coarse clay fractions. Coarse clay from suspended material at CBD-6 differed slightly from coarse clay at other locations in that it contained lower proportions of mica, kaolin and smectite and higher proportions of vermiculite-chlorite intergrade. Smectite and kaolin were the only phyllosilicate species detected in fine clay (< 0.2 µm) fractions of CBD samples in August, 1979. Smectite was clearly dominant in all cases and kaolin was present in moderate to abundant proportions in samples from CBD-1 through CBD-5. Kaolin was barely detectable in the fine clay of suspended material collected from CBD-6 during the normal irrigation season on August 9. Mineral species and their relative abundance in clay fractions of suspended sediments from CBD-1 through CBD-5 were found to be comparable to species and their relative abundance in the whole clay fraction (<2 µm) of bedload samples collected at CBD-1, CBD-2 and CBD-3 in June of 1979 and in whole clay fractions of suspended samples collected at CBD-1 and CBD-5 during the winter of 1979 (Tanji et al., 1980b). One potentially significant finding from mineralogical analyses was the fact that chlorite, abundant in most samples collected from the CBD was absent in bedload sediments and in suspended materials from all of the sampled feeder streams.

The mineralogical analyses of suspended and bedload materials did not provide information sufficient to allow assessment of the sources or sources of suspended mineral matter which contributes to turbidity in CBD. The general presence of chlorite in suspended and bedload materials within the drain and its absence in suspended and bedload materials from the feeder streams lends credence to the speculation that the chlorite component may derive from local sources within the Colusa Basin. Chloritization of expansible phyllosilicates in soils maintained under waterlogged conditions has been demonstrated by Lynn and Whittig (1966).

Phyllosilicate Species in Colusa Basin Soils--

Mineral matter suspended within CBD may derive from soils in upland watershed regions as a result of erosion and runoff during the rainy season, or from soils within the basin proper. In an attempt to establish evidence of source of suspended materials, clay fractions from surface horizons of five extensive soil series within the Colusa Basin were examined by x-ray diffraction.

Phyllosilicate species in the coarse and fine clay fractions of the soils were found to be similar both in kind and in relative proportions to phyllosilicate species suspended in CBD. Smectite, kaolin, mica and vermiculite-chlorite intergrade were found to be present in all soils in the drain. Representative x-ray diffractograms of clay fractions from one of the soils examined are shown in Fig. 27 for illustration.

The mineralogical analyses of the Colusa Basin soil clay fractions failed to provide definitive evidence of source of mineral matter suspended in CBD. Although clay mineralogy of soils and suspended materials were found to be similar, it cannot be concluded that the basin soils are the major source of the suspended mineral matter. The alluvium, which served as parent material for the Colusa Basin soils, was derived mainly from upland watershed areas. Therefore, the mineralogy of suspended materials within the drain and of the basin soils may both reflect the mineralogy of materials eroded from upland soils.

Soluble-Exchangeable Ion Relationships--

Electrical conductivities (EC) and concentrations of soluble cations and anions were determined for all suspensions collected for mineralogical studies. The data illustrate relationships between soluble and exchangeable ions adsorbed by suspended matter in CBD, as reflected by suspensions collected during January 1981.

Ca and Mg were the dominant soluble cations and bicarbonate (HCO_3) was the dominant soluble anion at CBD-6, the northernmost sampling location (Table 21). At all other locations, Na was the dominant soluble cation, and both HCO_3 and sulfate (SO_4) were prominent soluble anions. The Na concentration progressively increased in a southerly direction to a maximum at CBD-1. Soluble potassium (K) was consistently low at all locations.

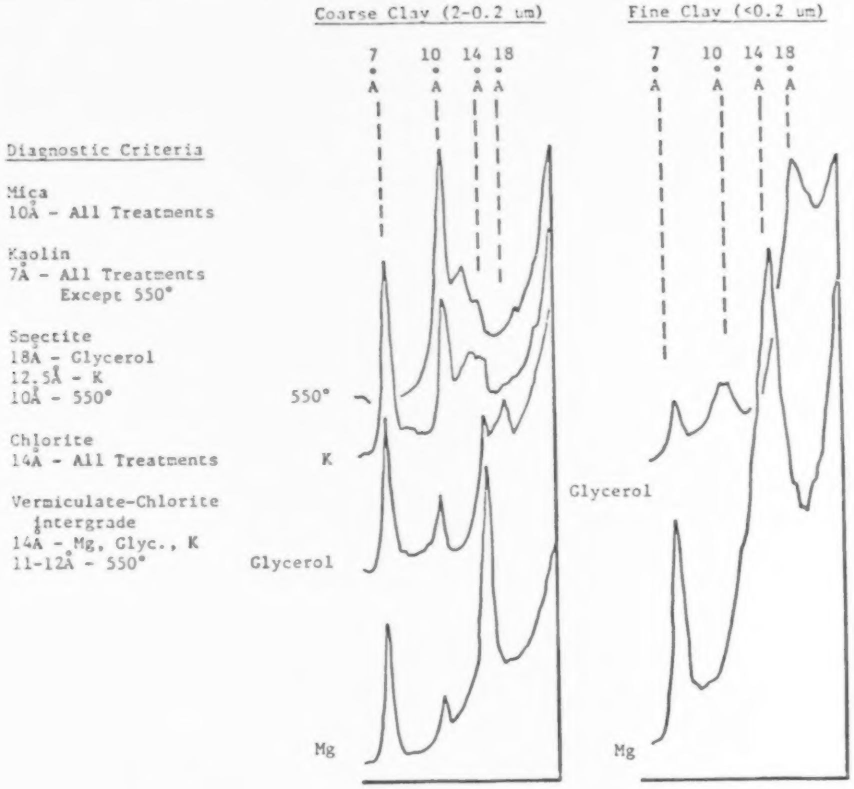


Figure 27. X-ray diffractograms of clay fractions of Willows clay (No. 124M) from the Colusa Basin.

TABLE 21. ELECTRICAL CONDUCTIVITIES AND SOLUBLE ION CONCENTRATIONS OF SOLUTIONS FROM COLUSA BASIN SUSPENSIONS – JANUARY 30, 1981

Sampling location	EC	Anions					Cations				
		CO_3	HCO_3	Cl	SO_4	Total	Ca	Mg	Na	K	Total
	μmhos/cm	meq/ℓ									
CBD-1	436	0	1.83	0.92	1.40	4.15	1.00	1.09	2.06	0.067	4.217
CBD-2	415	0	1.70	0.86	1.60	4.16	0.91	1.08	1.99	0.072	4.052
CBD-3	406	0	1.65	0.76	1.60	4.01	0.90	1.08	1.96	0.072	4.012
CBD-5	354	0	1.69	0.60	1.20	3.49	0.80	1.00	1.58	0.067	3.447
CBD-6	423	0	3.37	0.38	0.90	4.65	1.43	1.88	1.12	0.054	4.486

Ca and Mg were the dominant exchangeable cations adsorbed by suspended matter throughout the sampling transect (Table 22, 23). The relatively low exchangeable Na, in contrast to relatively high concentrations of soluble Na, indicate low Na adsorption specificity. Sediment, however, had a relatively high affinity for K adsorption. The data also indicated a higher adsorption specificity for Ca than for Mg.

TABLE 22. EXCHANGEABLE CATIONS AND CATION EXCHANGE CAPACITIES OF THE SUSPENDED SEDIMENTS – JANUARY, 1981

Sampling location	Exchangeable cations - meq/100 gr.					
	Ca	Mg	Na	K	Total	CEC
CBD-1	29.92	23.32	0.93	3.76	57.93	60.38
CBD-2	27.68	22.25	0.78	3.67	54.38	67.39
CBD-3	29.98	23.99	0.83	5.15	59.95	69.08
CBD-5	27.56	21.44	0.41	4.73	54.14	61.02
CBD-6	28.34	20.39	0.16	3.59	52.48	53.13

TABLE 23. RELATIONSHIPS BETWEEN SOLUBLE AND EXCHANGEABLE CATIONS IN SUSPENSION FROM COLUSA BASIN DRAINAGE AREA – JANUARY, 1981

Sampling location	Ca		Mg		Na		K	
	% of Total as							
	Sol.	Ex.	Sol.	Ex.	Sol.	Ex.	Sol.	Ex.
CBD-1	24	51	26	40	49	2	1	7
CBD-2	22	51	27	41	49	1	2	7
CBD-3	22	50	27	40	49	1	2	9
CBD-5	23	51	29	40	46	1	2	8
CBD-6	32	54	42	39	25	0	1	7

Cation adsorption specificities inferred from the above data were further demonstrated for Colusa Basin soil clays in separate experiments. A composited stock of clay extracted from the soils was used for the experiments due to limited quantities of clay in Colusa Basin suspensions. The mineralogy of the soil clays was similar to the mineralogy of suspended clays. Clays were equilibrated for 24 hours with mixed solutions of Ca-Mg, Ca-Na, and Mg-Na. Equilibration solutions were prepared to provide various cation ratios for each mixed cation pair ranging from 1:00-0.00 to 0.00-1.00. Total concentrations of all solutions were maintained at 25 meq/ℓ, and the pH of the solutions adjusted to 5.0. Cations in solution and adsorbed phases were determined after the equilibration periods.

Preferential adsorption of Ca from mixed Ca-Mg solutions was clearly exhibited by Colusa Basin soil clay equilibrated with 25 meq/ℓ Ca-Mg solutions (Tanji et al., 1981). Preferential adsorption of Ca was most pronounced for systems where the equivalent fraction of Ca and Mg were in intermediate ranges. Preferential adsorption of Ca and of Mg was exhibited by soil clays equilibrated with Ca-Na and Mg-Na solutions (Tanji et al., 1981). The degree of adsorption specificity was about the same for both Ca and Mg. The data indicated a small but perceptibly strong adsorption affinity for Na even when the equilibration solutions contained a low equivalent fraction of Na. This signified the presence of Na-specific exchange sites within the mineral complex of the soil clays. The identity of the Na-specific exchange sites could not be ascertained from data obtained.

Water Quality Survey

A water quality survey was conducted on selected stations along the drain and tributaries for chemical factors affecting dispersion, flocculation, and sedimentation of suspended particles in the drain. Salinity, sodium absorption ratio (SAR), EC, pH of the water, and nutrients were studied and are reported in the annual reports to EPA (Tanji et al., 1978, 1980a, 1980b).

The salinity of waters was measured in terms of total dissolved solids (TDS). Three years of data on TDS gave values ranging from 200 to 800 mg/ℓ, an average of 400 mg/ℓ, at CBD-1, and lower values at the other stations. The salinity of the water was generally lower during the storm runoffs and during August from the dilution resulting from high winter runoff and drainage from the rice fields, respectively. The concentrations of dissolved ions in the system did not have an effect on flocculation.

The EC of storm runoff waters ranged from 140 to 440 μmhos/cm. The average EC of the supply water (main canal) was 195 μmhos/cm. The EC of the drain water ranged from 460 to 1,170 μmhos/cm. There was a tendency for salinity to increase from CBD-6 (upstream) to CBD-1 (downstream).

SAR of the supply water and the drain water was measured to study the dispersive effect of sodium on suspended charged particles. Chemical analysis indicated that SAR ranged from 0.5 in the supply water to 6.0 in some tributaries or creeks. The average value of SAR was 2.5 in stations along CBD. From data collected during the 1978 and 1979 summers, the SAR increased from the main supply canal to CBD, and remained relatively constant along the drain.

The effect of pH on pH-dependent charges was important where 40 percent of supended particles were organic matter. Since the pH of water in the study area was greater than 7.0, all organic particles in the drain were $R\text{-}COO^-$ negative charged and behaved as clay particles. The alkaline pH of CBD waters had an important effect on the stability of the suspended particle.

The pH values ranged from 7.4 to 8.5 for all water samples from the study area, the cation concentrations ranged from 1.2 to 9.0 meq/ℓ, and the SAR ranged between 0.5 to 6.0. Considering the mixture of kaolinite, illite, vermiculite, montmorillonite, and organic particles present, the effect of

SAR, cation concentration, and pH on either flocculation or dispersion are considered negligible in this study.

Hydrobiological Survey

Biological factors affecting sediment production in CBD were studied in detail during the 1978 and 1979 summers. Sampling was conducted to study the effects of biological organisms on sediment production in CBD (Hayes et al., 1978). Sampling sites were three stations along the drain (CBD-1 to CBD-3) and from two tributaries (Stone Corral Creek at Two Mile Road and the Glenn-Colusa Irrigation District Main Canal). The factors studied are reported in detail in the annual report to EPA (Tanji et al., 1978, 1980a).

The factors controlling the suspended particle transport, deposition, and resuspension are physical, chemical and mineralogical, and biological. The chemical and mineralogical factors did not appear to have a significant effect on the suspended sediment flocculation, deposition, and dispersion in this study. Based on the physical factors of current velocity and resulting shear stress of flow, the suspended sediment concentration should decrease from CBD-2 to CBD-1 because the current velocity and bed shear stress were always lower at CBD-1 than at CBD-2. The summer study in 1978 and 1979 showed that suspended sediment was constantly greater at CBD-1. Since there was no other source of sediment contributing to the drain between CBD-2 and CBD-1, the difference may be attributed to the biological activities of bottom-dwelling organisms.

Species of fish captured during the summer study are listed in the annual report to EPA (Tanji et al., 1980a). The Asiatic clam was the most abundant benthic organism in the drain. Most of the benthic organisms collected from the drain do not have a significant effect on sediment production. The exception are the carp (*C. carpio*) and crayfish (*O. viriles* and *P. clarkii*). Carp have bottom-feeding habits and are known to increase turbidity through resuspension of finer particles while foraging. Crayfish also cause resuspension of sediments by their burrowing activity and general locomotion. The contribution of biological activities in suspended sediment was evaluated through calibration of the sediment transport model. It was estimated that aquatic organisms contributed between 0 to 20 percent of the total suspended sediment (Mirbagheri and Tanji, 1981).

Pesticide Residue Survey

One of the problems associated with the production of return flow water from agricultural areas is the transport of agricultural chemicals in the water and suspended sediments. Both surface and subsurface flows are of interest although the latter are more difficult to evaluate. The transport of pesticidal chemicals is of continuing concern where crops are grown and pest control involving both weeds and insects is required. Pesticides for the control of insects and weeds include a large number of organic compounds. They differ widely in their chemical and toxicological characteristics, in their behavior and in their impact on the environment. In contrast to other agricultural chemicals, their impact is often greater even though the concentrations are exceedingly small by comparison.

The target organism or the chemical nature of the compounds may determine how the chemical is categorized. Chemicals may be grouped according to whether they are herbicides, insectidices, nematicides, organochlorines, organophosphates or carbamates. Their physical, chemical and biological properties vary over a wide range. These properties range from soluble to insoluble in water, volatile to nonvolatile, photochemically sensitive to insensitive, and microbially resistant to readily degraded. They must be toxic to target pests to be effective. This toxicity may have immediate or chronic effects often through bioaccumulation in the organisms.

Since soil as well as water is often involved in the ultimate deposition of these compounds, the interaction and processes that occur in the soil environment may have significant effects on their behavior in the environment. The movement of chemicals into drains and other water conveyence systems may involve aqueous phase transport as well as the movement with soil materials eroded into the water course. Since a dynamic relationship exists between the adsorbed and aqueous phase chemical concentration, the mixing of eroded materials containing adsorbed chemical with the drain water will result in changes in the concentration of chemical in the two phases. The deposition of sediment and degradation of the chemicals, if they occur, will further modify the chemical concentration in the aqueous phase subject to transport. While analysis of this complex system was beyond the scope of the present investigation, attempts have been made to monitor inputs of chemicals to CBD at selected locations, evaluate the sediment-aqueous chemical concentrations, and examine spatial distribution and time dependent changes at selected sites.

Selection of Chemicals--

Based on surveys of pesticide use in the study area prior to 1980, it was evident that Molinate and 2-methyl-4-chlorophenoxyacetic acid (MCPA) represent chemicals extensively used in the study area. This was further confirmed by compilation of records for 1980 from the County Commissioners for Colusa and Yolo Counties. A total of 74,505 kg of active ingredient MCPA was applied for weed control principally in rice and wheat crops. In the same two counties, 228,510 kg of Molinate was applied principally in rice for weed control. A third chemical, Ethyl Parathion, was selected for its potential impact in a different manner on aquatic systems. In this case the target organism is shrimp in rice crops. A total of 1310 kg of Ethyl Parathion was applied in 1980. In 1981 attention was directed to Methyl Parathion due to its extensive use.

A brief description of the chemicals follows (Pesticide Manual, 1971):

MCPA or 2-methyl-4-chlorophenoxyacetc acid, is a herbicide of formula $C_7H_9ClO_3$ and molecular weight (m.w.) 200.5. In pure form it is a white crystalline solid of melting point (m.p.) 118°C, with a solubility in water of 825 parts per million (ppm) at room temperature. Some other names are 4-chloro-o-toloxyacetic acid, 4-chloro-o-cresoxyacetic acid, and MCP.

Molinate or S-ethyl hexahydro-1H-azepine-1-carbothioate, is a herbicide of formula $C_9H_{17}NOS$ and m.w. 187.3. In pure form it is a clear liquid of boiling point (b.p.) 137°C at 10 mm mercury (Hg), and has a solubility in water of 900 ppm at 21°C. It is also known as "Ordram."

Ethyl Parathion or 0,0-diethyl o-p-nitrophenyl phosphorothioate, is a nonsystemic contact insecticide of formula $C_{10}H_{14}NO_5PS$ and m.w. 291. The pure form is a pale yellow liquid of b.p. 157 to 162 at 0.6 mm Hg, with a solubility in water of 24 ppm at 25°C. A commonly used name is "Parathion."

Methyl Parathion or 0,0-dimethyl o-p-nitrophenyl phosphorothioate, is a nonsystemic contact insecticide of formula $C_8H_{10}NO_5PS$ and m.w. 263. The pure chemical is a white crystalline power of m.p. 35°C, and its solubility in water is 60 ppm at 25°C.

Procedures for Sampling and Analysis--

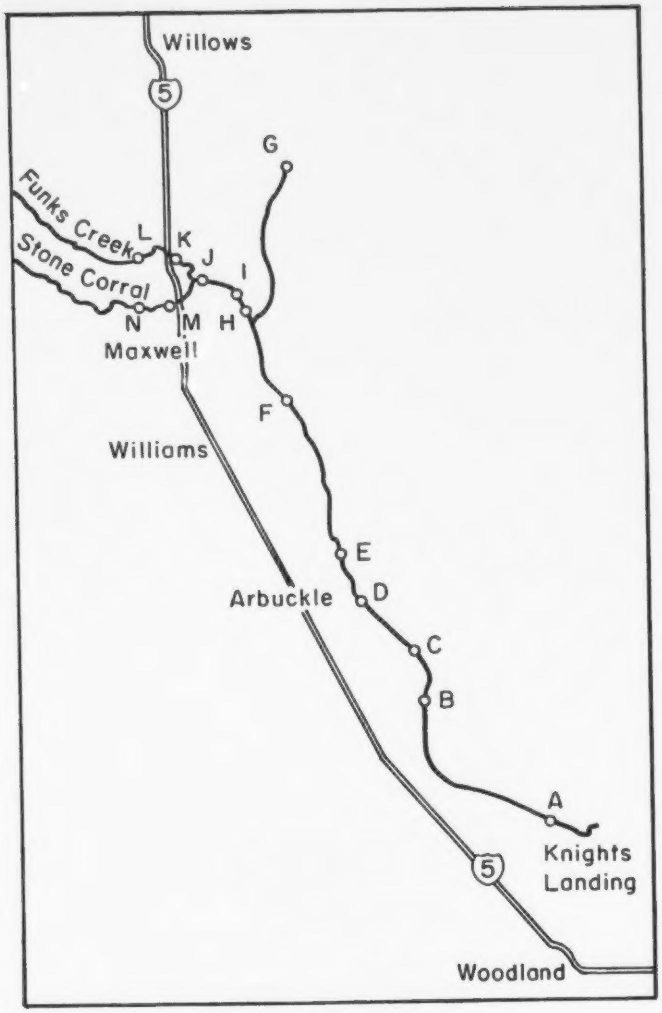
Samples were collected in 2 liter teflon-capped glass jugs prepared by sequential water, acetone and pesticide-quality hexane rinses followed by drying. They were transported immediately in a dark environment and stored at 8°C until extraction commenced within 72 hours. Extracts were analyzed immediately or stored at 8°C in the dark until analysis. The procedures for sampling and analysis were reported in the annual report to EPA (Tanji et al., 1980b).

Extraction procedures were specifically formulated to extract Molinate since preliminary laboratory observations indicated that only Molinate appeared in sufficient concentrations for detection in the sediment. Three liter water/sediment samples were acidified and filtered through celite. The sediment-containing celite was homogenized in acetone using a probe type high speed homogenizer. The resulting acetone slurry was filtered, and the filtrate concentrated at <40°C in a rotary evaporator. The concentrate was passed through a C-18 Sep-Pak cartridge, and the retained Molinate eluted from the cartridge for analysis. The samples were analyzed by gas-liquid chromatography using Electron-Capture detectors for MCPA, and Thermionic-Specific- or N-P-detectors for Molinate, Ethyl and Methyl Parathion.

Study Area – Sampling Stations--

The selection of sampling stations was based on previous experience as reported in the annual report to EPA (Tanji et al., 1980b) (Figure 28).

In addition to providing information on the chemical status of the drain over considerable distances, a more detailed examination is provided by sites on Funks Creek and Stone Corral Creek prior to their discharge into the CBD. Water flow and water quality parameters which may have an impact on chemical movement were measured at these stations. Coordination of sampling for various water quality parameters and pesticides in a temporal and spatial program were facilitated by these selected stations.


Willows
5
G
Funks Creek
L
K
J
I
Stone Corral
N
M
H
Maxwell
F
Williams
E
Arbuckle
D
C
B
A
Knights Landing
5
Woodland

1980-81 Pesticide Survey Stations

Figure 28. 1980-81 Pesticide Survey Stations: A = CBD-1; B = CBD-2; C = CBD-2A; D = CBD-3; E = CBD3A; F = CBD-5; G = CBD-6; H = Stone Corral Creek (SCC) at Maxwell; I = SCC at 4 Mile Road; J = SCC at 2 Mile Road; K = Kunks Creek at Lenahan Weir; L = Funks Creek at McDermott Road; M = SCC at Frontage Road; N = SCC at McDermott Road.

Analysis of Sample Station Waters--

In 1980 the chemicals Molinate, MCPA and Ethyl Parathion were determined, and Methyl Parathion was added in 1981. Flow data and suspended sediment at the same stations and time are included. The maximum concentration of Molinate was measured on May 12, 1980, at Stone Corral Creek at Maxwell Road. This maximum was an order of magnitude greater than most other samples containing appreciable Molinate for which there is no explanation. In general, Molinate concentrations began to increase in late April or early May, increasing to a maximum in early June and declining thereafter. Concentrations usually increased to between 200 and 300 parts per billion (ppb) before declining to undetectable levels.

The chemical MCPA exceeded 3.0 ppb on only one occasion. This occurred on June 22, 1981, at CBD-6 at Stone Corral Creek at Frontage Road. A maximum concentration of 26.9 ppb of MCPA found in discharged waters was measured in an outfall station near Stone Corral Creek at McDermott Road on September 8, 1980. During the two-year study the maximum concentration of 18 ppb Ethyl Parathion was measured at CBD-6 on May 11, 1981. All other concentrations were less than 1.0 ppb, and most less than 0.1 ppb. During the 1981 season analysis for Methyl Parathion revealed a maximum concentration of 120 ppb at CBD-6 on May 11, 1981, the same time and location of the maximum concentration of Ethyl Parathion. Although Methyl Parathion appeared more frequent at higher concentrations in the waters than Ethyl Parathion, the concentrations were less than 16 ppb and usually less than 5 ppb. Both Ethyl and Methyl Parathion appeared in drain waters during the period of May to July, 1981.

The concentrations of Molinate for each of the stations as a function of time for the 1980 and 1981 seasons were compared. The emission of Molinate or its occurrence in the drain waters was measured at approximately the same time period in both years, indicating a constancy in cultural practice. The maximum concentrations measured were greater in 1981, suggesting a possible increase in chemical use although water outflow at the time of chemical use could also influence the levels found. While the patterns of emission at each station are similar they are sufficiently different to indicate the influence of site specific factors. The fact that the patterns of emission are similar at various locations along the drain at about the same time indicates that emissions are occurring along the drain and are not associated with emissions from a particular area to be dispersed in the direction of flow. Major differences in emission between the two years are evident in the concentrations measured in Stone Corral and Funks Creeks, the two sources investigated off the main drain.

Molinate Concentration and Water Flow--

Since the flow of water in the CBD reflects the discharge of water from various sources into the drain and the emission of Molinate is probably related to the spillage of water from surrounding areas, the concentrations of chemical in the drain may be related to changes in flow in the drain and its tributaries. These effects were examined for 1980 and 1981 at various stations. While some stations indicate increases in flow and chemical concentration during similar time periods in both years, the agreement is less evident for others. Differences in the flow regime between years are evident as illustrated by CBD-1, CBD-2 or CBD-2A. Increases in chemical emission with increases in spillage can only occur if the chemical is present at the time of spillage, thus reflecting the influence of cultural practices on chemical emission. It is particularly important to avoid spillage of water to drains during the period when chemical applications occur. A correlation between Molinate emission and flow at all stations as shown in Figure 29 is not as evident as might be anticipated. The lack of correlation is probably related to the large number of sampling periods when chemical was not present, or present at low concentrations. The correlation is improved when examined at individual stations suggesting the site specific nature of the process, but sufficient data at individual stations were not available to substantiate the sigificance of the correlation. The random nature of the timing of chemical application and timing of spillage which account for inputs to the drain partially explains the lack of correlation observed.

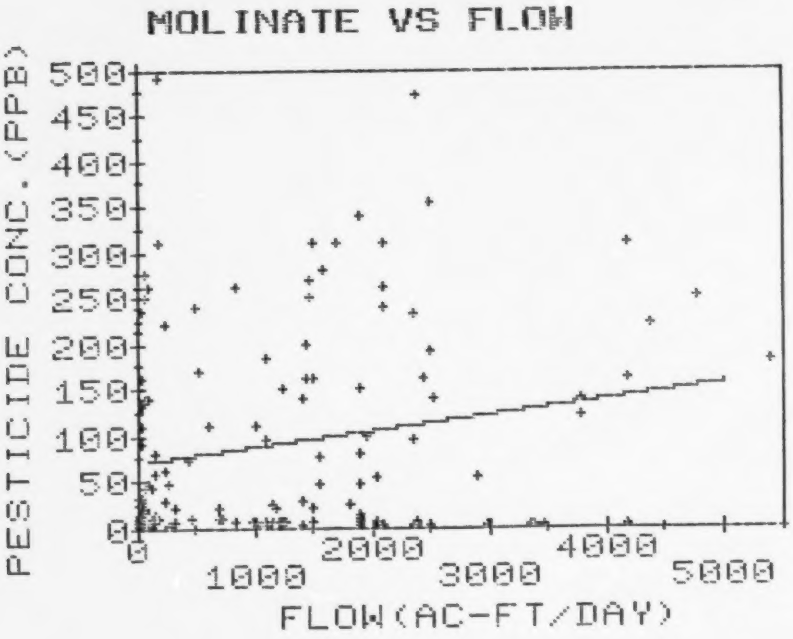


Figure 29. Concentration of Molinate as a function of water flow at several stations in the Colusa Basin Drainage area including data for 1980 and 1981.

Molinate Emission and Suspended Materials--

The movement of water in the area served by the CBD is the major vehicle by which all forms of chemicals and suspended matter are transported through the system. It is known that chemical transport occurs both in the aqueous phase and adsorbed to the suspended matter in the aqueous phase. The dynamic relationship between the concentration of chemical in the two phases may be important in determining the disposition of the chemical temporally and spatially, and the impact it has on the environment. Consequently it was of interest to examine the chemical and suspended sediment concentrations as a function of time. Other investigations in this project have shown the relationships that exist between flow and concentration of suspended matter.

As was the case with Molinate concentration and flow, there appears to be some correlation between chemical concentration and suspended matter concentrations at some of the stations while at others the relationship is less evident. This might be expected since other processes in addition to flow are involved in the manner by which Molinate and suspended matter are introduced into the flow regime, mixed, and transported. An additional factor is the dynamics of adsorption and desorption between the adsorbed and aqueous concentrations of Molinate in the water transport system. Consequently the interaction of all these complex processes results in a low correlation between Molinate concentrations in the aqueous phase and the concentration of suspended matter as shown in Figure 30.

Since the total emission of Molinate depends upon the amount carried in the suspended matter as well as in the aqueous phase, it was of further interest to examine the relative concentrations that exist in the two phases in the drainage waters. Additional samples were collected at the sampling stations on three different occasions during a period when chemical outflow was occurring. The suspended matter was separated from the aqueous phase and the concentration of Molinate in the two phases determined.

The results of this investigation are given in Table 24. It is noted that the suspended material content in the samples varied from 12 to 96 ppm so that the material to water ratio varied by eightfold. In agreement with adsorption phenomena of most pesticides on surfaces, the concentration of Molinate in the adsorbed phase is several fold larger than that in solution, with the increase in adsorbed chemical decreasing as the corresponding concentration in solution increases. This fact is demonstrated in Figure 31 where adsorbed concentration is larger at smaller solution concentrations, and increased at a decreasing rate as solution concentration increased, reaching an approximate plateau at 300 ppb in the aqueous phase and 1000 ppb in the suspended material. It should be noted that the relationship shown in the figure is based on samples taken from 14 different locations on three different sampling periods. When the ratio, MO_s/MO_w, of the concentration of Molinate in the suspended matter to the concentration in the aqueous phase was calculated as shown in Table 25, this "preference" or "adsorption" ratio varied over a wide range. While the ratio may be somewhat affected by the variation in concentration of the suspended matter, it most likely reflects the differences in the nature of the suspended matter and adsorbing surfaces.

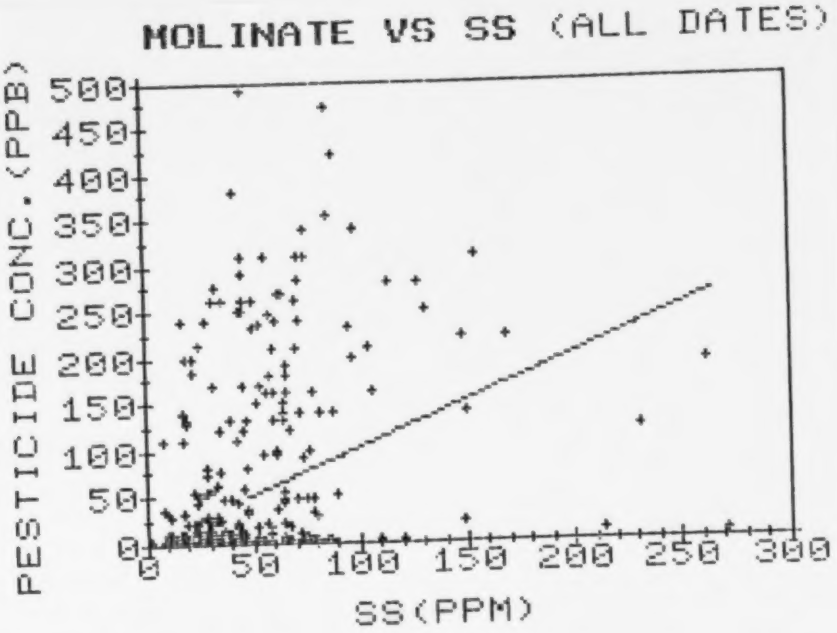


Figure 30. Concentration of Molinate as a function of suspended sediments in samples collected at various stations in the Colusa Basin Drainage area including data from 1980 and 1981.

Both organic and inorganic materials constitute the suspended matter as described elsewhere in this project, and the relationship between the adsorbed and solution concentrations will vary depending upon the nature of the adsorbing surfaces and relative concentrations of differing adsorption materials. It is interesting to note that the ratio increased as the season progressed from May 25 to June 16.

In view of the large concentration of Molinate in the suspended matter relative to that in the aqueous phase, it might be concluded that emission of Molinate in suspended matter could constitute an important vehicle for transport in the water system. This was not generally the case since the quantity of suspended matter relative to the water phase was small. This showed that chemical emission in the suspended material was insignificant relative to that in the solution phase. If conditions are such that the concentration of suspended matter is large and sufficient chemical are present to approach saturation of the solid phase, then emission in that phase relative to the solution phase might become significant. As indicated previously, the nature of the adsorbing surface would be important.

No assessment was made of the relative environmental impact of the chemical in the solution phase and the adsorbed phase. Processes affecting

TABLE 24. SUSPENDED MATTER AND MOLINATE CONCENTRATIONS IN SUSPENDED MATTER AND SOLUTION IN DRAINAGE WATERS COLLECTED AT 14 SAMPLING STATIONS AT THREE SAMPLING TIMES IN THE COLUSA BASIN DRAINAGE AREA

Sampling Date	5/25/81			6/8/81			6/16/81		
Sample station	Suspended matter (ppm)	MO_w[1/] (ppb)	MO_s[2/] (ppb)	Suspended matter (ppm)	MO_w (ppb)	MO_s (ppb)	Suspended matter (ppm)	MO_w (ppb)	MO_s (ppb)
CBD-1	96	230	938	20	199	1000	23	52	870
CBD-2	62	238	968	23	182	435	29	55	1030
CBD-2A	86	352	1050	62	94	806	26	23	769
CBD-3	86	472	930	18	109	536	34	23	588
CBD-3A	46	289	870	20	126	500	35	24	571
CBD-5	72	283	972	66	178	909	47	35	851
CBD-6	34	276	882	78	48	769	12	11	-
SSC/MAX	58	247	690	47	131	851	31	13	323
SCC/4 MI	54	234	741	57	160	702	36	14	556
SCC/2 MI	51	233	980	35	121	1140	18	10	-
SCC/FRONT	23	199	1300	8	34	-	16	10	-
SCC/McD	26	212	769	10	33	-	18	8.7	-
FUNKS/LEN	21	9.7	476	24	<1.0	-	50	<1.0	-
FUNKS/McD	36	10.7	278	49	<1.0	-	32	<1.0	-

[1/] MO_w = molinate concentration in the aqueous phase

[2/] MO_s = molinate concentration in the suspended matter the transport of the chemical associated with the suspended material may be different from that in the solution phase since sedimentation may occur. Processes of degradation and dissipation depend upon the phase in which the chemical is present and its subsequent impact on nontarget organisms. Assessment of the chemical outflow relative to water and suspended material movement from agricultural fields would suggest that application of chemical during periods of spillage of water into drains and other water conveyance systems should be avoided. Increasing the residence time of water in the field during and following applications for some reasonable period should be helpful.

Time-Dependent Survey--

Pesticide concentrations at a given station depend upon factors that involve water discharge and other cultural practices, as well as time of application of the chemical. The time at which samples are obtained during short-term fluctuations could have significant effects on chemical concentrations measured. This is in contrast to many other water quality parameters that are measured. To ascertain the fluctuations in chemicals over the period of a day, samples were collected at various times on May 11, 1981, at CBD-1, a period when Molinate and Methyl Parathion were present. Station

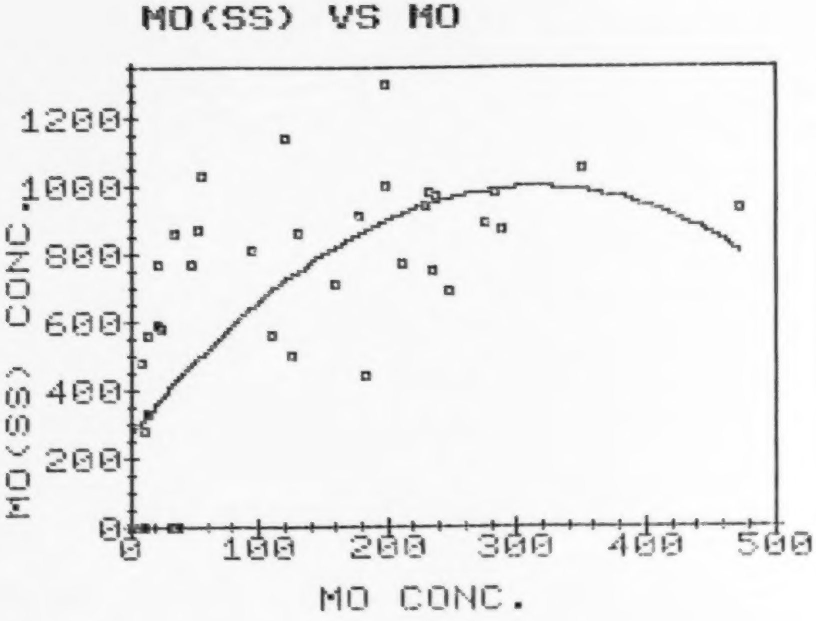


Figure 31. Concentration of Molinate in the suspended matter as a function of Molinate concentration in the aqueous phase determined on samples taken at three sample times from 14 sample stations in the Colusa Basin Drainage area as given in Table 24.

Table 25. The ratio of Molinate concentration in the suspended matter to the Molinate concentration in the aqueous phase (MO_s/MO_w) for sampling stations and times given in Table 24.

Sample date	5/25/81	6/8/81	6/16/81
Sample station	MO_s/MO_w	MO_s/MO_w	MO_s/MO_w
CBD-1	4.08	5.03	16.73
CBD-2	4.07	2.39	18.73
CBD-2A	2.98	8.57	33.43
CBD-3	1.97	5.10	25.57
CBD-3A	3.01	3.97	23.79
CBD-5	3.43	5.11	24.31
CBD-6	3.20	16.02	-
SCC/MAX	2.79	6.50	24.85
SCC/4 MI	3.17	4.39	39.71
SCC/2 MI	4.21	9.42	-
SCC/FRONT	6.53	-	-
SCC/McD	3.63	-	-
FUNKS/LEN	49.07	-	-
FUNKS/McD	25.98	-	-

CBD-1 was selected because it represents an integration of inputs and processes that occur upstream, and is the last station prior to discharge to the Sacramento River.

Table 26 presents results for the two chemicals, water flow, and suspended sediment. While flow decreased to midday and then increased, the opposite is true for suspended sediment. Molinate and Methyl Parathion showed a midmorning and midafternoon decrease from higher concentrations in the morning, at noon and late afternoon. Concentrations of Molinate ranged from a minimum of 33 to a maximum of 220 ppb during the day while Methyl Parathion ranged from 3.0 to 5.9 ppb. These fluctuations are probably associated with various processes that occur upstream, and demonstrate the order of magnitude of fluctuations at a station that is less likely to be unduly influenced by a particular event where flows are smaller and perturbations are larger. The example serves as further evidence of the complexity of the system.

Spatial Survey--

A spatial survey of a limited reach of Stone Corral Creek was attempted in July 1981 to examine changes in sediment and aqueous phase chemicals over a short period of time. The location selected coincided with an earlier study of sediment production in Stone Corral Creek. This one-mile stretch

Table 26. Fluctuations in flow, suspended sediments, Molinate and Methyl Parathion at CBD-1 during the period from 8:00 AM to 4:30 PM on 5/21/81.

Time (hour)	Flow (cfs)	Suspended sediment (mg/ℓ)	Molinate (ppb)	Methyl Parathion (ppb)
08:00	1262	156	278.0 269.5	4.2 4.2
10:30	1165	210	222.8 220.4	3.2 3.2
12:30	1074	338	322.8 325.4	5.8 5.9
14:30	1474	208	234.7 234.0	3.0 3.0
16:30	1364	182	337.3 33.3	4.2 4.2

has well defined inputs (runoff) from agricultural fields and is easily accessed at any point from a parallel road. Samples were to be analyzed for residues in both the aqueous and suspended sediment phases.

The outflow stations to the Creek were identical to the previous sediment production study, but the stations along Stone Corral Creek were selected to be evenly spaced at 0.1-mile intervals (Figure 32). The inputs are described in the annual report to EPA (Tanji et al., 1978).

For unknown reasons, the input stations R11, R12, R13, and R14 remained dry until the latter part of the month. By this time, pesticide levels had decreased to near detection levels as shown in Table 27. Inconclusive results were obtained other than an indication that inputs even at these low levels affect the concentration in the creek.

COMPUTER SIMULATION MODEL AND USER'S MANUAL

A computer simulation model for the transport of mineral and organic forms of suspended matter was formulated and validated. Figure 33 shows the general structure of the model.

Transport Equation

The transport equation is based on the mass balance for a substance given as:

$$\text{Accumulation} = \text{Inflow} - \text{Outflow} \pm \text{Sources or Sinks} \qquad (10)$$

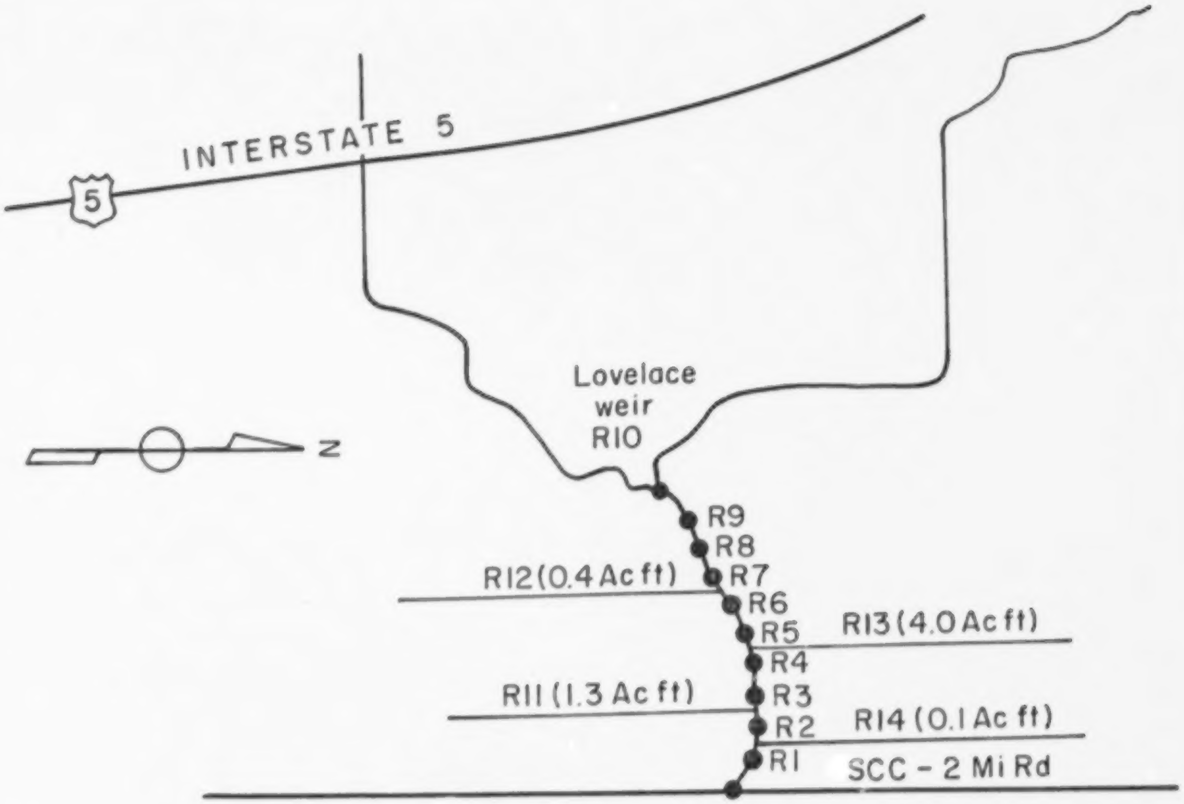

INTERSTATE 5
5
N
Lovelace
weir
R10
R9
R8
R7
R6
R5
R4
R3
R2
R1
R12 (0.4 Ac ft)
R13 (4.0 Ac ft)
R11 (1.3 Ac ft)
R14 (0.1 Ac ft)
SCC - 2 Mi Rd

Figure 32. Spatial Survey Stations.

TABLE 27. SPATIAL SURVEY OF PESTICIDE AND SUSPENDED SEDIMENT IN A ONE-MILE REACH OF STONE CORRAL CREEK IN JULY 1981

Station	Suspended sediment (mg/ℓ)	Pesticide	
		MCPA (ppb)	Methyl Parathion (ppb)
Inputs			
R11	15.0	<3.0	<0.1
R12	9.0	<3.0	1.3
R13	9.5	24	<0.1
R14	27.4	16	<0.1
Creek			
R10	25	<3.0	1.0
R9	24.5	<3.0	1.0
R8	22.0	<3.0	1.0
R7	19.5	<3.0	1.0
R6	20.0	<3.0	1.0
R5	31.0	<3.0	0.7
R4	30.5	3.8	0.3
R3	34.5	5.0	<0.1
R2	31.5	3.9	0.3
R1	31.0	6.9	0.3
Output			
Stone Corral Creek at Two Mile Road	26.5	7.3	0.6

The mass balance equation can be developed for a particular substance by considering advective transport, diffusive transport, erosion and deposition, chemical and biological transformations, and lateral inflow of point and nonpoint sources.

The CBD was monitored at selected stations in a cross section and vertical plane for suspended mineral sediment, suspended algae, suspended organic matter, and nutrients. The results showed a small variation vertically and laterally for all parameters from the surface to a three-foot depth. From actual measurements it was assumed that the dominant mass transport mechanisms in CBD are in the horizontal plane. The advection-diffusion of suspended mineral and organic matter of uniform size, shape, and density are considered in a one-dimensional uniform flow. The basic mass balance equation for all constituents can be written by assuming a steady state, nonuniform, spatially varied stream flow as follows:

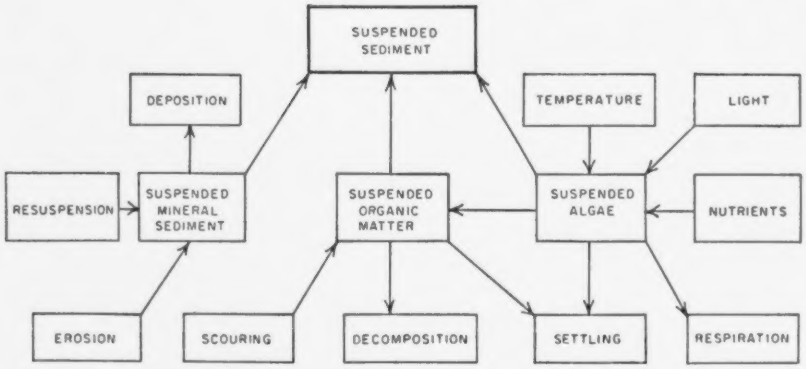

SUSPENDED SEDIMENT
DEPOSITION
TEMPERATURE
LIGHT
RESUSPENSION
SUSPENDED MINERAL SEDIMENT
SUSPENDED ORGANIC MATTER
SUSPENDED ALGAE
NUTRIENTS
EROSION
SCOURING
DECOMPOSITION
SETTLING
RESPIRATION

Figure 33. General model structure.

1. Mass balance equation for suspended mineral sediment

$$\underset{(a)}{\frac{\partial s_m}{\partial t}} = \underset{(b)}{- \frac{1}{A} \frac{\partial}{\partial x} (AUS_m)} + \underset{(c)}{\frac{1}{A} \frac{\partial}{\partial x} \left(AD_x \frac{\partial S_m}{\partial x} \right)} + \underset{(d)}{\frac{1}{A} \frac{dS_m}{dx}} + \underset{(e)}{\frac{dS_m}{dt} \bigg|_e} - \underset{(f)}{\frac{dS_m}{dt} \bigg|_d} + \underset{(g)}{K_r} \qquad (11)$$

where:

S_m = concentration of suspended mineral sediment (mg/ℓ)
A = cross-sectional area (ft^2, m^2)
U = average stream velocity (fps, mps)
D_x = diffusion coefficient (m^2/sec)
x = distance (mile, km)
t = time (sec)
K_r = resuspension coefficient.

In equation (11), (a) represents the rate of change of concentration, (b) represents transport due to longitudinal advection, (c) represents transport due to longitudinal diffusion, (d) represents the lateral inflow of point and nonpoint sources, (e) represents the process of erosion, (f) represents the process of deposition, and (g) represents the process of resuspension.

The erosion of the bed material can be defined as a process of detachment and translocation of sediment particles by the forces of water. In equation (11) the term erosion is given as:

$$\left.\frac{dS_m}{dt}\right|_e = M \left(\frac{\tau_b}{\tau_c} - 1 /d \right) \tag{12}$$

where

M = erodibility constant
τ_c = critical shear stress (dyne/cm^2)
τ_b = bed shear stress (dyne/cm^2)
d = local depth of water (ft, m).

The deposition of suspended particles occurs when the shear stress of the flow on the bed is less than the critical shear stress. In equation (11) the deposition is given as:

$$\left.\frac{dS_m}{dt}\right|_d = \frac{2v_s S_m}{y} \left(1 - \frac{\tau_b}{\tau_c} \right) \tag{13}$$

where

v_s = settling velocity of the suspended particle (ft/sec)
y = depth through which the particle settles (ft, m).

The last term in equation (11) takes into account the resuspension of bed materials through biological activities. The resuspension coefficient, K_r, was evaluated from the comparison of suspended sediment between CBD-2 and CBD-1.

The bed shear stress, the critical shear stress, and the erodibility constant were described in detail in Water Science and Engineering Paper No. 4021 (Mirbagheri and Tanji, 1981).

2. Mass balance equation for suspended organic matter

$$\frac{\partial S_{om}}{\partial t} = - \frac{1}{A} \frac{\partial}{\partial x} (AUS_{om}) + \frac{1}{A} \frac{\partial}{\partial x} \left(AD_x \frac{\partial S_{om}}{\partial x} \right) + \frac{1}{A} \frac{dS_{om}}{dx} - (K_1 + K_2) S_{om} + S_c + S_{ra} \tag{14}$$

S_{om} is suspended organic matter. The term S_c is the rate of additions of organic matter to the overlying water by resuspension of deposited organic matter. The term S_{ra} represents the contribution of dead algae to the suspended organic matter through respiration. K_1 is the BOD decay coefficient in mg/ℓ per day. The rate coefficient K_2 is the settling rate of organic matter.

The mass balance equations were developed for suspended algae, concentrations of ammonia, nitrate, and orthophosphate. The coefficients were evaluated and reported in Water Science and Engineering Paper No. 4021 (Mirbagheri and Tanji, 1981).

Solution Technique

The numerical technique consists of replacing all derivatives with an implicit finite-difference quotient, and differential equations with algebraic equations. The different variables involved are varied continuously with distance (x) and time (t). In a finite difference scheme, the value of each variable is computed for a finite set of coordinates x and t. To facilitate the computation, it is convenient to draw a uniform grid (Figure 34) of points in the x-t plane, with intervals Δx and Δt, and to compute the values of the variables for each point.

Subscripts i and j are used to denote grid points having coordinates $(i - 1)\Delta x$ and $(j - 1)\Delta t$ which leads to $S(x_i, t_j)$ where S is the constituent concentration.

Equations (11) and (14) can be rewritten as mass balance equation

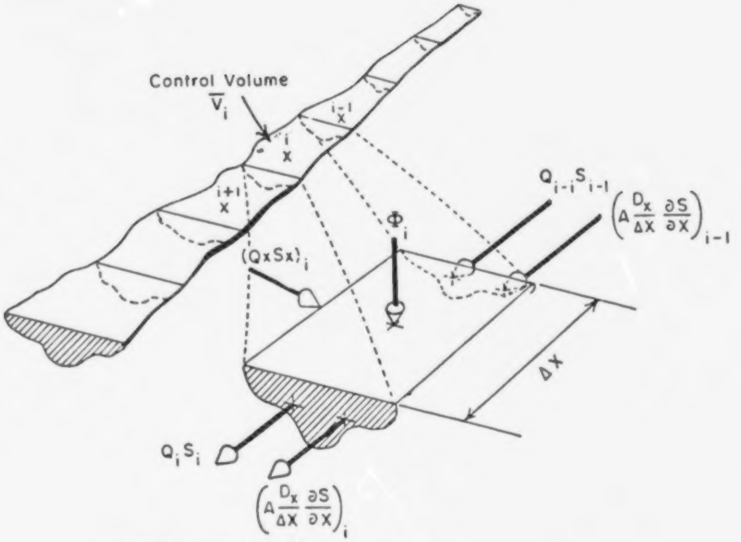
$$\frac{\partial S}{\partial t} = - \frac{1}{A} \frac{\partial}{\partial x} (QS) + \frac{1}{A} \frac{\partial}{\partial x} \left(AD_x \frac{\partial S}{\partial x} \right) + \phi \qquad (15)$$

where S is the concentration of variables involved in the computation and ϕ represents sources and sinks. A computer program was developed to solve equation (15) for suspended mineral sediment, suspended organic matter, suspended algae, and nutrient.

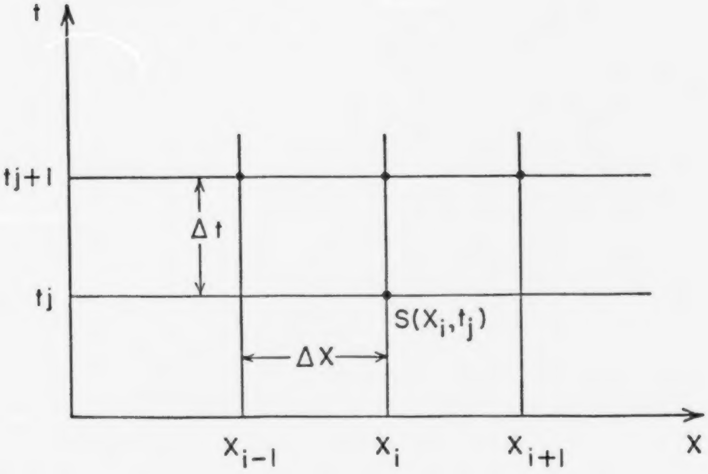
Model Application, Validation, and Sensitivity Analysis

Application--

The model developed was applied to CBD. Figure 34 shows a portion of CBD used for model application. The selected stretch of CBD is 20 miles long. It extends from CBD-3 (Tule Road) at mile 25 to CBD-1 near Knights Landing at mile 5. The tributary inflows not under control are treated as incremental flow of water and sediment into the system. CBD-2 was treated as flow entering the system or the upper boundary, and CBD-1 was the outflow from the system.


Control Volume
$\overline{V}_i$
x^{i-1}
x^{i}
x^{i+1}
$Q_{i-1}S_{i-1}$
$\left(A\frac{D_x}{\Delta x}\frac{\partial S}{\partial x}\right)_{i-1}$
Φ_i
$(Q_x S_x)_i$
Δx
$Q_i S_i$
$\left(A\frac{D_x}{\Delta x}\frac{\partial S}{\partial x}\right)_i$

MATERIAL BALANCE


t
tj+1
Δt
tj
$S(X_i,t_j)$
ΔX
X_{i-1}
X_i
X_{i+1}
X

Temporal and Spatial Grid points

Figure 34. Discretized stream system after Water Resources Engineers, Inc. (1976).

Validation

For model calibration and validation as shown in Figure 35, the 20 mile lower reaches of CBD were divided into five equally spaced parts, and six sampling sites: CBD-3, CBD-2a, CBD-2, CBD-1b, CBD-1a, and CBD-1. Each reach was divided into eight computational elements having separate hydraulic, physical, biological, and chemical characteristics. This particular division was based on the channel uniformity and axes to set up the sampling sites.

The input data to the model are the channel cross section measured at the sampling sites, the hydraulic data, the sediment and nutrient data. Hydraulic data are the flow rate, the current velocities, and the water depth measured at each station. The weekly values of mean velocity and water depth for three years were plotted against discharge (Mirbagheri and Tanji, 1981).

A hydraulic balance was established at each reach between consecutive sampling stations. The flow entering the system from the farthest upstream (CBD-3) was measured. The net inflows were computed by flow differences at all other stations. Additional flows between the stations were input to the model as incremental flow.

During the 1980 summer, extensive sampling and measurement of suspended mineral sediments, suspended organic matter, suspended algae, ammonia, nitrate, orthophosphate, light intensity, and temperature were conducted from CBD-3 to CBD-1. These parameters were measured for three consecutive days at the surface, 1 secchi-disc depth, and 2 secchi-disc depth. The average value for three depths was used. The current velocities were measured at two stations. The average velocity between the stations was calculated. The sampling time interval for each station was calculated from the average velocity and the distance between the two stations. The water entering the system at CBD-3 was considered for measurement of all parameters. It was monitored from one station to the next. It took approximately 15 hours for the water to enter upstream and leave downstream. The routing time for the model was considered to be 15 hours. The parameters measured at CBD-3 were used as input data, or the boundary condition for the model. The parameters measured at CBD-2a, CBD-2, CBD-1b, CBD-1a, and CBD-1 were used to calibrate and validate the model. The measured data is tabulated in Water Science and Engineering Paper No. 4019 (Tanji et al., 1980b).

Simulation Results

The measured and simulated sediment and nutrient concentration profiles along CBD were compared to determine the accuracy of the simulations. Figures 36 through 38 show the results of the hydraulic, suspended sediments, and nutrient simulations. Table 28 summarizes the measured and simulated data.

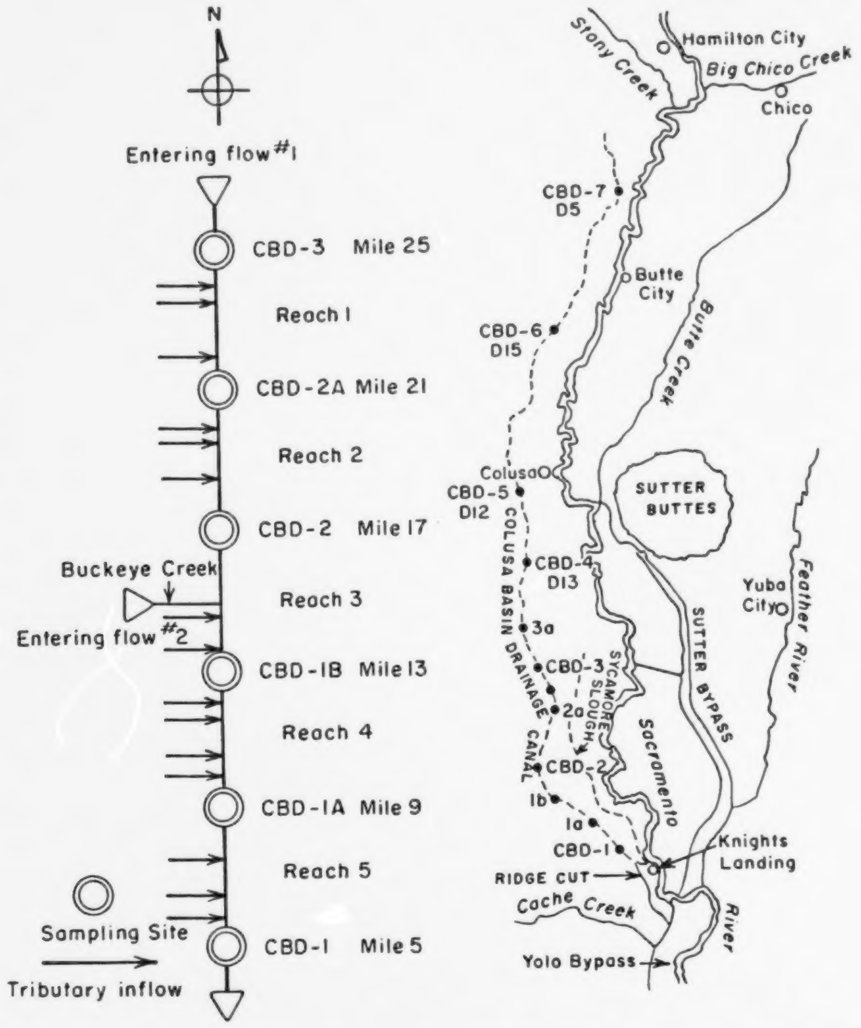

N
Entering flow #1
CBD-3 Mile 25
Reach 1
CBD-2A Mile 21
Reach 2
CBD-2 Mile 17
Buckeye Creek
Reach 3
Entering flow #2
CBD-1B Mile 13
Reach 4
CBD-1A Mile 9
Reach 5
Sampling Site
Tributary inflow
CBD-1 Mile 5
Stony Creek
Hamilton City
Big Chico Creek
Chico
CBD-7
D5
Butte City
Butte Creek
CBD-6
D15
Colusa
CBD-5
D12
SUTTER BUTTES
CBD-4
D13
Yuba City
Feather River
COLUSA BASIN DRAINAGE CANAL
SUTTER BYPASS
3a
CBD-3
SYCAMORE SLOUGH
2a
Sacramento
CBD-2
1b
1a
CBD-1
Knights Landing
RIDGE CUT
Cache Creek
River
Yolo Bypass

Figure 35. Location map of sampling station and the reaches in CBD.

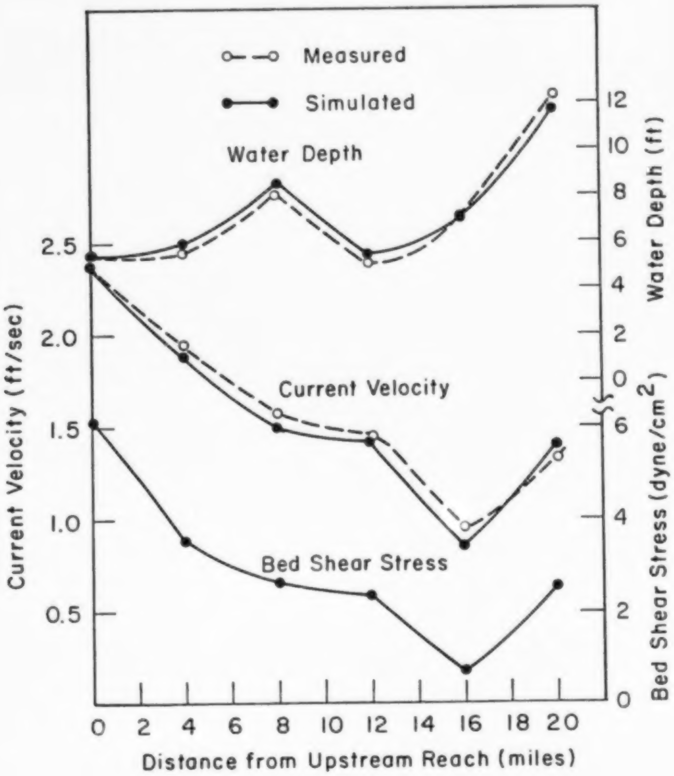


Figure 36. Hydraulic parameters simulation results.

Figure 36 shows an agreement to the simulated values (solid line) with the measured values (dotted line) for current velocity and water depth. The models were developed from the rating curves used for the simulation of current velocities and water depth. Figure 36 shows that the simulated values for the bed shear stress and current velocity follow the same pattern.

Three fractions of suspended sediment simulated were suspended mineral sediment (SM), suspended organic matter (SOM), and suspended algae (SA). The total suspended sediment is expressed as TSS = SM + SOM + SA. Figure 37 shows the simulation values of SM to be 90 ±5 percent of measured values. It shows the simulation for SOM agrees with the measured values. The simulated and the measured curves for TSS follow the same pattern. The general behavior of the prototype is represented well by the model output.

Suspended algae was simulated by developing regression and dynamic models. Figure 38 shows simulated values of suspended algae. The first solid line corresponds with the dynamic model, the second solid line

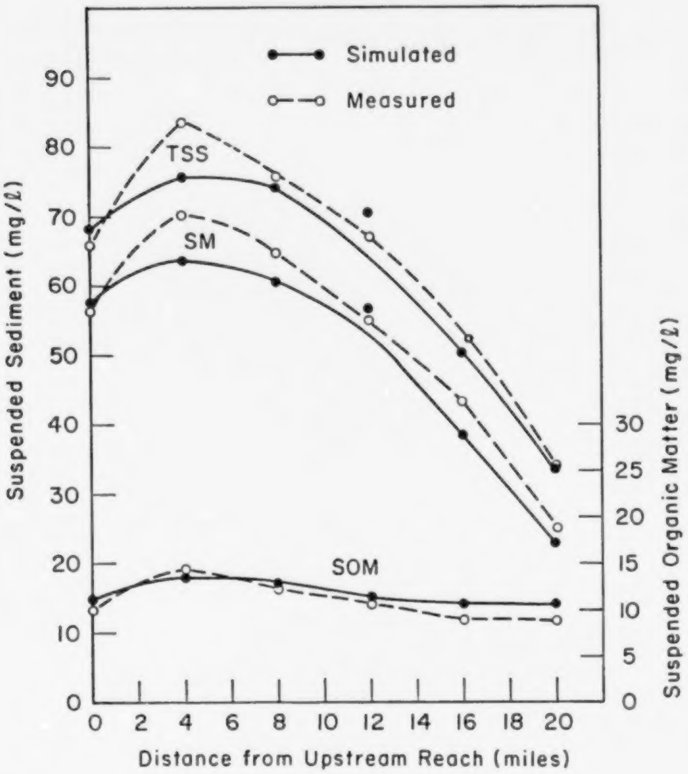


Figure 37. Suspended sediments simulation results

corresponds with the regression model, and the dotted line is the measured value. Both models followed basically the same pattern when compared with the measured value in simulating suspended algae. The concentration of orthophosphate in the regression model controls algal biomass by 80 percent while not affected by light. The dynamic model considers the effect of light intensity in the water and the concentration of orthophosphate. Light was considered in the dynamic model in the event the model is used for locations where light is the limiting factor for algae growth.

Algae simulated by the regression model is closer to the measured value than the dynamic model. Figure 38 shows that the regression model overestimated the value of suspended algae from CBD-1a (mile 16) to CBD-1 (mile 20) possibly due to high nitrate concentrations. The algal biomass should increase with time and distance. A decrease was noted between CBD-2a (mile 4) and CBD-1b (mile 12), and followed by an increase. This was due in part to endogenous respiration and the settling rate of algae, and the lateral inflow of algae from the rice fields between CBD-1b and CBD-1.

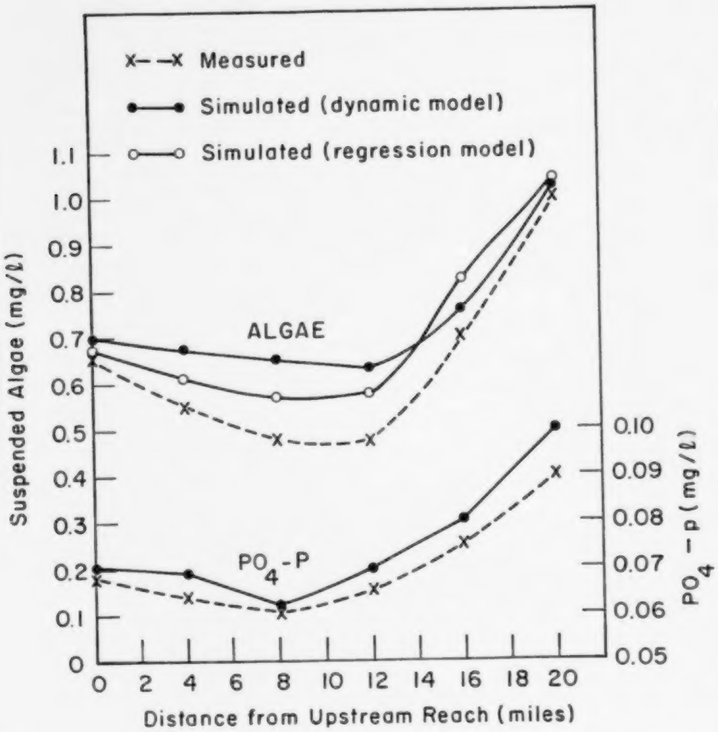


Figure 38. Algae and phosphorus simulation results.

Figures 38 and 39 show simulation of orthophosophate, ammonia, and nitrate. The simulated and measured values of orthophosphate and ammonia are similar. Figure 39 shows that the simulated data on nitrate overpredicted the concentration from CBD-1a (mile 16) to CBD-1 (mile 20). A large amount of terrestrial and aquatic plants grow on the bank and in the water in this reach. The nitrate uptake by these plants was not considered in the model. There is no data available on the biomass of these plants. The concentration of nitrite was negligible.

Sensitivity Analysis

The model was more sensitive to the changes of some coefficients. In the suspended sediment simulation, the current velocity controlled the bed-shear stress and consequently, the process of erosion. In the suspended organic matter simulation, the current velocity controlled the scouring coefficient. The model was calibrated with a flow rate of 1,500 cfs, the average flow rate for the irrigation season. In the simulation of total

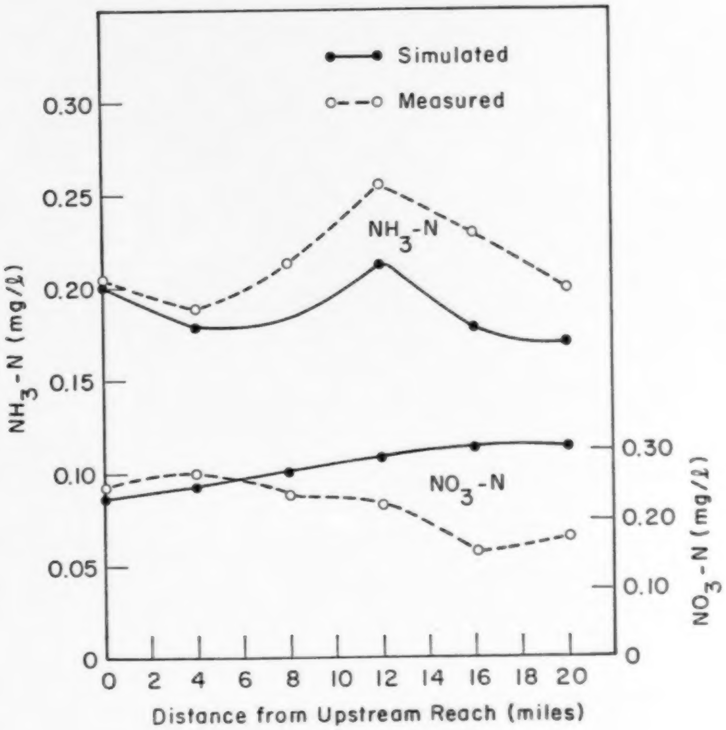


Figure 39. Ammonia and nitrate simulation result.

suspended sediments for the sensitivity analysis, the model was operated on a flow rate of 5,000 cfs, the maximum flow rate for the irrigation season. A rise from a flow rate of 1,500 cfs increased the current velocity from 1.80 fps to 3.8 fps. The bed shear stress increased from 3.4 to 13.5 dyne/cm^2. With a critical shear stress at 10 dyne/cm^2, the process of deposition at a flow rate of 1,500 cfs changes to erosion at a flow rate of 5,000 cfs.

The model is sensitive to the settling velocity of particles in the transport process, the flow rate, current velocity, and the bed shear stress. The settling velocity was doubled while other factors remained the same as the base value. The suspended sediment decreased by 40 percent. The settling velocity is important for the deposition rate. Similarly, the bedshear stress is important for the erosion rate. The model is sensitive to both factors.

Sensitivity analysis was conducted on the concentration of suspended organic matter. The three factors contributing to the suspended organic

TABLE 28. SUMMARY OF MEASURED AND SIMULATED DATA FOR MAXIMUM FLOW OF 1500 CFS

	SM (mg/ℓ)		SOM (mg/ℓ)		SA (mg/ℓ)			TSS (mg/ℓ)		NH_3 (mg/ℓ)		NO_3 (mg/ℓ)		PO_4 (mg/ℓ)		Velocity†		Water depth§		TSST	
Stations	M	S	M	S	M	S	S_r	M	S	M	S	M	S	M	S	M	S	M	S	M	S
CBD-3	57.0	58.1	10.0	10.8	0.66	0.70	0.68	67.0	68.6	0.20	0.20	0.23	0.22	0.068	0.07	2.37	2.37	5.5	5.50	235	241.5
CBD-2A	70.0	62.1	14.0	12.5	0.53	0.69	0.61	84.0	75.0	0.19	0.18	0.24	0.23	0.065	0.07	1.80	1.75	6.0	5.70	306	270.8
CBD-2	63.0	60.1	12.0	12.0	0.46	0.68	0.57	75.0	74.0	0.22	0.19	0.22	0.24	0.06	0.06	1.56	1.49	8.0	8.50	283	275.3
CBD-1B	54.0	57.2	10.5	11.8	0.45	0.67	0.58	67.0	70.0	0.26	0.21	0.21	0.25	0.065	0.07	1.48	1.41	5.5	5.48	271	294.8
CBD-1A	43.0	34.5	9.0	11.0	0.70	0.76	0.84	52.0	47.0	0.23	0.18	0.15	0.26	0.075	0.08	0.82	0.71	7.0	7.10	203	188
CBD-1	25.0	22.0	9.0	11.0	1.0	1.04	1.03	33.0	34.0	0.20	0.17	0.18	0.26	0.09	1.0	1.35	1.40	12.0	11.95	142	1382

† measured in fps; § measured in ft; T measured in tons/day.

SM = suspended mineral sediment
SOM = suspended organic matter
SA = suspended algae
TSS = total suspended sediment
NH_3 = concentration of ammonia

NO_3 = concentration of nitrate
PO_4 = concentration of phosphate
M = measured
S = simulated
S_r = simulated using regression model

matter changes along the drain are decay rate (K_1), settling rate (K_2), and scouring. K_1 was reduced to one half the base value. The simulation values of organic matter increased by 15 percent, with all factors remaining constant. The same response was observed by reducing K_2 to one half of the base value.

Sensitivity analysis was performed on the model for the simulation of suspended algae. The three factors contributing to suspended algae concentration in the system are specific growth rate controlled by the phosphorus half saturation constant (K_p), endogenous respiration (RE), and algae settling rate. The simulated profile of algal biomass was increased by 100 percent by decreasing K_p from 0.25 to 0.05 mg/ℓ per day. Algal biomass decreased by 20 percent as the respiration rate and the settling rate increased by two from the base value.

User's Manual

A user's manual describing the computer program, flow charts, and the program listing was developed and presented in Water Science and Engineering Paper No. 4021 (Mirbagheri and Tanji, 1981).

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